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ASSESSMENT OF NATIONAL RESEARCH TRENDS FOR DEVELOPMENT OF UNMANNED GROUND VEHICLES

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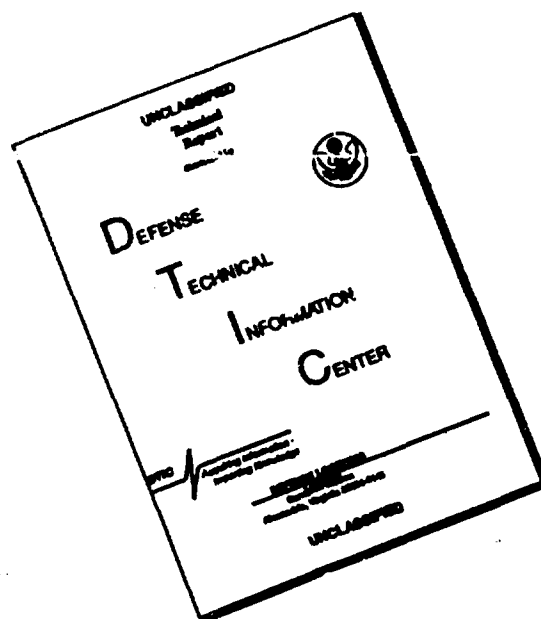
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PART I. DISCUSSION AND RESULTS

1.0 INTRODUCTION

Robotic vehicle research and development is progressing in several application areas which include airborne, space, underwater, and terrestrial. Terrestrial applications include uses within constrained environments, such as inside buildings, as well as outdoor applications, such as on roads or across open areas. Research and development in these areas is supported by industry (oil exploration, warehousing, etc.), civilian government (DOE, NASA) and DOD (Army, Navy and Air Force). The purpose of this study is to understand national research trends within certain technical areas, specifically: sensors, perception algorithms, cognitive algorithms, and the necessary supporting hardware that can enable the fielding of practical autonomous systems for land warfare. This report presents the findings of this study regarding the status of national research trends in these areas and offers some suggestions regarding future development of unmanned vehicles based on these trends.

Technology advances in microelectronics, composite materials, electro-optics, sensors, micromechanics, computer power, and artificial intelligence have made unmanned military ground vehicle development and utilization possible. Although there is a vast amount of robotics research and development occurring, there has never been an attempt to organize an understanding of current research trends. Since it is necessary to make informed decisions regarding technologies specifically required for unmanned ground vehicles (UGVs), it is important to understand which technologies are and are not being addressed by other application areas or by other organizations.

The hazardous environment of many military unmanned vehicle applications necessitate some very different requirements than those of civilian applications. In many cases, a military vehicle will have to operate in a hostile environment on paths and around obstacles that have never been encountered previously. A military vehicle must also be prepared to counter or avoid detection, threats or hostile action, where an intelligent adversary is purposely attempting to thwart the vehicles progress. However, Army/Marine ground applications also have similar needs in technology as other applications. These common technology areas include real time data links for communication and control, image transmission, and a capability for performing some level of autonomous monitoring and task performance.

Therefore, the objective of this study is to develop an understanding of national research and development trends in robotics and how these trends compare to needed technologies for the unmanned ground vehicle application. Recommendations will also be made regarding which technologies require more attention than they are now being given in order to achieve an unmanned vehicle capability for the ground forces and assure that all technologies required are matured as needed. These recommendations will account for common areas of research where duplication need not occur, such as communication and image transmission.

Cost and mission performance are the predominant considerations in the development, implementation, and operation of unmanned ground vehicles. In almost any day to day operation, manpower is the most costly expense. Cost effective UGVs used as a force multiplier could greatly decrease operational costs. Cost and other systems related issues will be a significant factor in our assessment of technologies and achievable capabilities.

2.0 ANALYSIS METHODOLOGY FOR UNMANNED GROUND VEHICLE OPERATION

This section provides a framework for understanding how robotic and UGV technologies are to be classified and understood in the context of this study. This study requires that an assessment be made of existing technologies in order to develop and understand desired research and development goals. Therefore, an exposition of how robotics is viewed is necessary before the given assessment of UGV related research can be appreciated. This exposition will be presented in section 2.2.

The focus of the present study is on how to achieve autonomous vehicle navigation. There is some debate within the community over precise definitions, therefore this report will reference the definitions that are given in the subsections that follow.

What will be presented next is a short discussion on the following topics:

- Levels of Autonomy.
- Technologies required to achieve various levels of autonomy.
- Assessment methodology and factors considered in the assessment.

2.1 LEVELS OF AUTONOMY

The level of human control varies between two extremes that we call *direct* control and *indirect* control. In the candidate definitions outlined below, *control* implies what we term *direct* control: control exerted by an operator on the actions of an unmanned ground vehicle via a real-time direct link.

The definitions must be further clarified by stating that *autonomy* is not a single concept. For purposes of this study, we will separate *rote* autonomy from *intelligent* autonomy. The former refers to the ability to carry out a task without external control, but only in a preprogrammed, non-adaptive, fashion. Intelligent (or cognitive) autonomy implies the ability to successfully execute tasks in real-world and therefore uncertain circumstances, such that the task environment cannot be adequately predicted for preprogramming. For autonomous navigation applications, we are concerned with intelligent autonomy and operating in an uncontrolled environment.

In the lexicon of this report, there are six forms of control that will be considered. They are:

- 1) Telepresence
- 2) Teleoperation
- 3) Teleassistance
- 4) Guided robotics
- 5) Supervised robotics
- 6) Autonomous robotics

What follows is a more descriptive narrative of what these definitions mean.

- *Telepresence*

In both telepresence and teleoperation, an operator has full control of all vehicle functions, from navigation and driving functions through mission activities. In neither case does the introduction of robotics reduce manpower requirements: both are limited to a 1:1 operator:vehicle ratio. We distinguish the two modes, not by the degree of operator control, but by the sophistication of feedback provided to the operator.

Telepresence denotes a mode of operation in which an attempt is made to provide full sensory simulation such that the operator feels "present" at the scene. Telepresence is therefore characterized by elaborate sensing and communications requirements in order to simulate the sensory experience. The communications load and sophistication of the operator/vehicle interface for telepresence suggest that this type of operation may be reasonable only for very complex or delicate tasks to be conducted in hazardous environments, i.e. when the sensory input is necessary for mission execution and the risks incurred by a person performing the mission outweigh the cost of a highly sophisticated interface.

- *Teleoperation*

In teleoperation, a reduced amount of feedback is provided to the operator. The interface supplies substantial information to the operator, but not necessarily in the form which would be experienced during direct operation. For example, information may be restricted to a single modality (e.g., video) or summarized (e.g., a pressure readout rather than tactile feedback). Teleoperation places lower demands on communication channels than telepresence and may have reduced sensor requirements. However, depending upon the information needed by the operator teleoperation may require more on-board computing for preprocessing sensor and vehicle data.

Examples of *Teleoperation* are:

- TOV, a Marine Corps technology demonstrator of the late 80's (see section 7.9.2).
- TMAP, an Army technology demonstrator of the late 80's (see section 7.8)
- The Surrogate Test Vehicle (STV), used in the pre-milestone II phase of the tactical unmanned ground vehicle (TUGV) acquisition program to assess, jointly with the users – Army infantry and Marine Corps – operational benefits and liabilities of a teleoperated reconnaissance, surveillance, and target acquisition (RSTA) UGV and to serve as a platform for demonstrating in a military system configuration the maturity of teleassistance technologies considered for the engineering and manufacturing development (EMD) of the TUGV (see section 5.1).

- *Teleassistance*

In teleassisted operation, the vehicle is primarily operator-controlled, but a limited set of functions are left to the control of the machine. In principle, these functions may be mission-related and/or related to the navigation task. All actions are monitored by the operator and operator intervention is possible in all functions. Because of the level of interaction and control required of the operator, teleassistance limits an operator to a single UGV. Relegation of some tasks to machine control, however, may reduce training requirements and operator workload and may improve performance in stressful environments. The operator interface and communication requirements can be relaxed from those of teleoperation with a corresponding increase in on-board computing requirements.

Examples of *Teleassistance* are:

- JPL's Computer Aided Remote Driving (CARD) programs, either CARD I or CARD II. The vehicle assists the operator in some low level functions, especially in low level navigation and obstacle detection. Retrotraverse, where a vehicle can retrace a route that was directed by a human, is also an example of teleassistance. Retrotraverse does not require machine intelligence to plan the original route.
- Demo I (see section 5.1.2.1)

- *Guided Robotics*

Guided robotics is distinguished from teleassistance by a decrease in the amount of control exerted by the operator. In guided robotics, low level functions are entirely machine-controlled while control of high level functions is retained by the operator. Certain functions are monitored only at the request of the vehicle. The transition from teleassisted to guided robotics incorporates the first elements of true autonomy. The vehicle must carry out certain functions without operator oversight and therefore is required to monitor its own performance well enough to request guidance or intervention when necessary. In relieving the operator of low level functions, guided robotics affords the first opportunity for force multiplication through control of more than one vehicle by a single operator.

Examples of *Guided Robotics* are:

- JPL's Semi-autonomous Navigation (SAN) program. The vehicle-landing craft exploration system itself takes important steps in path planning under the guidance of a human remote operator. It is significant that this vehicle is aimed at space exploration in which cost is far less important than system failure.
- DARPA's Autonomous Land Vehicle (ALV) program

- *Supervised Robotics*

Supervised robotics represents a substantial increase in autonomy over guided robotics. The operator retains control of only the highest level functions, which may be exercised intermittently. As a consequence, control of multiple vehicles by a single operator becomes practical; this level of autonomy has the potential for substantial force multiplication. Accompanying the increased sophistication of the machine capability is a significant reduction in communication and interface requirements. This level of autonomy enables us to partition the workload between the machine intelligence (MI) of the UGVs and the human supervisor such that the capability of both are optimally used; e.g., all routine work is done by MI. The human handles only those tasks for which the AI technologies, that are required to approximate human capability to integrate and exercise control authority, do not yet exist.

Examples of *Supervised Robotics* are:

- DOD planned DEMO II program (see section 5.1.2.2)

- *Autonomous Robotics*

Autonomous robotic performance is, by definition, operation without external control. Operational communication and interface requirements are not at issue, except from the standpoint of testing and validation. Autonomy does not preclude the possibility for preplanning by an operator, but does require that a machine be able to carry out a mission without requiring intervention. The requirements for *intelligent* autonomous capability are not completely understood, but include the ability to adapt to environmental changes and to acquire missing information. The requirements for *rote* autonomy are, of course, significantly less.

There are no known examples of *Autonomous Robotics* within our definitions.

2.2 FUNCTIONAL PROCESSES FOR AUTONOMOUS OPERATION

To achieve autonomous movement, there are three functional processes required that are interrelated. They are:

- 1) Perception: Sensing and low level (high volume) data processing algorithms and technologies.
- 2) Cognition: High level (abstract) symbolic processing
- 3) Action: Movement, employment of reconnaissance, targeting or weapons.

Perception includes algorithms and technologies that allow an unmanned vehicle to perceive (model) its surroundings, its position and identify hostile threats and other situations that occur during a mission. Cognition is a classical definition that includes both planning and learning. Cognition allows a robot to *understand* its relationship to its surroundings and

how to plan its movements in order to achieve its objective. It could be said that this requires awareness and judgement. Planning can be extended to also mean mission specific understanding besides navigation, for instance, understanding when to engage weapons or employ active Reconnaissance, Surveillance, and Target Acquisition (RSTA) sensors to best advantage. Learning is the reasoning required for automatic planning to achieve specified objectives. Action allows a robot to actually achieve its goals, such as movement over rough terrain, or employment of sensors and weapons. Research related to mobility platforms would be included in the category of action technologies.

Figure 1 graphically illustrates the relationship between these three parts of the robotic process, as it is defined in this report.

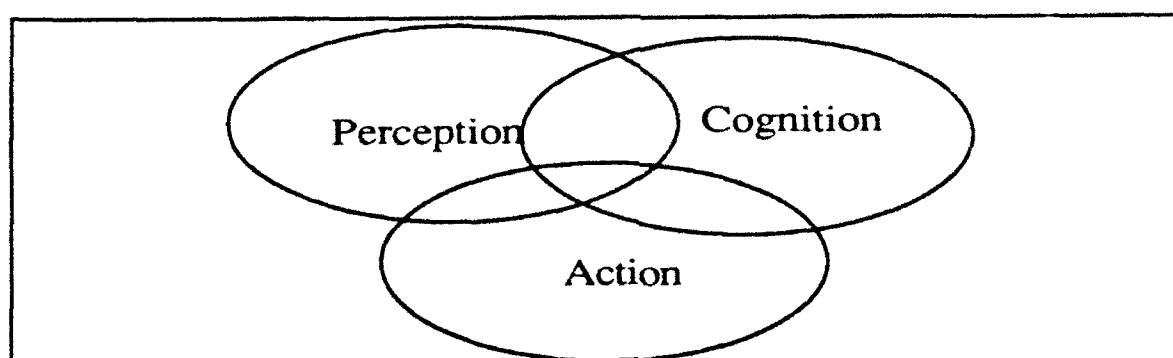


Figure 1. Process Required for Autonomous Navigation.

These functional processes are at the highest level of abstraction, and need to be developed further before specific research strategies can be analyzed.

It is somewhat intuitive that the field of robotic technology for ground warfare must necessarily evolve from technologies that employ high levels of interaction with operators to more autonomous applications. Any one of the functional processes of perception, cognition, and action can employ human intelligence, especially perception and cognition. Automating these functions will eventually lead to the "brilliant" weapons that will act as effective force multipliers for the ground forces. Figure 2 illustrates the relationship of functional processes, human interaction, and employment of a ground vehicle.

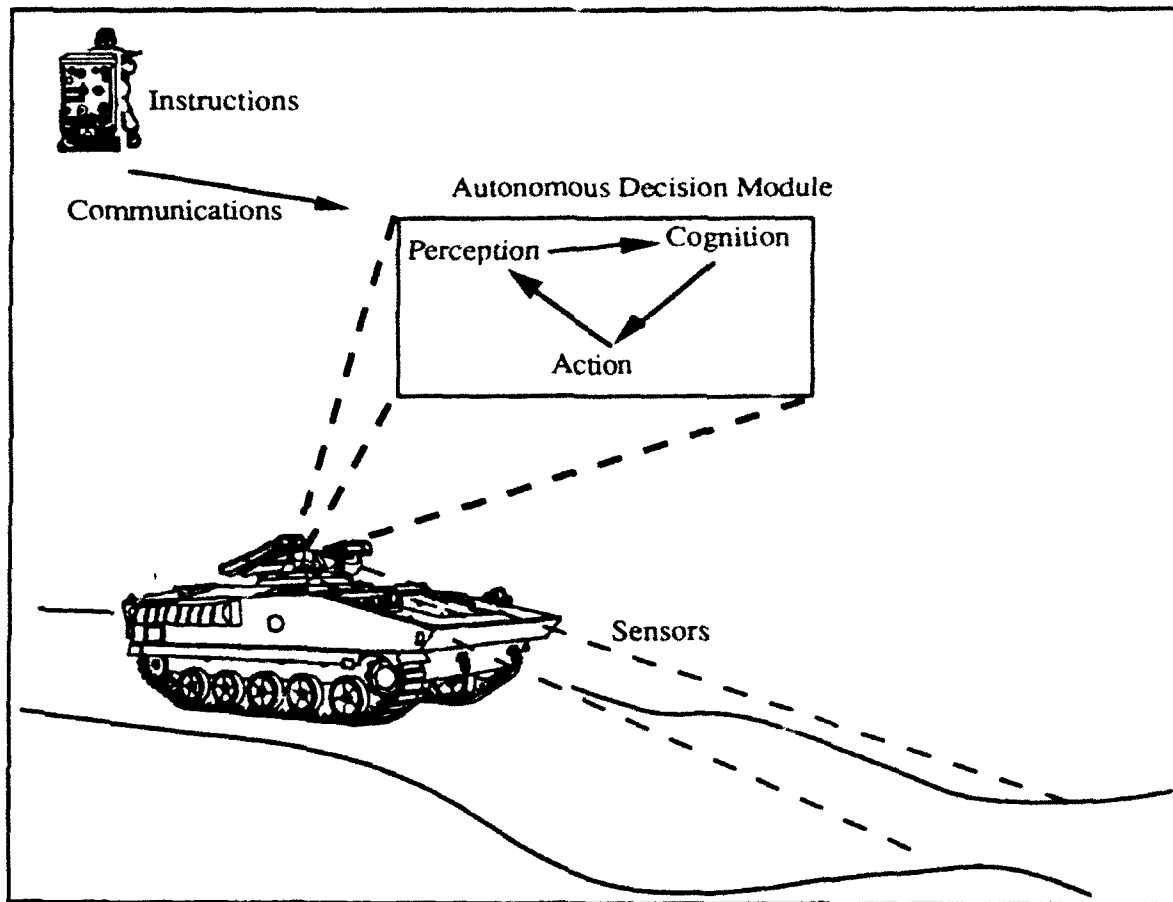


Figure 2. Interaction of Human, Machine, and a Ground Vehicle.

Perception involves sensing the surroundings of a UGV and processing what is sensed into a form that facilitates decision making. Technologies that will contribute to this process, then, are sensors, sensor preprocessing of data, computer vision algorithms, and computer vision processing architectures. To understand this group of technologies, some exposition is useful.

A common assumption in the robotics community is the utility of the human vision paradigm. This assumption asserts that if human vision can be mimicked, then the obvious utility of our superior vision system can be brought to bear in robotic applications. The term that will be used to describe this paradigm in the rest of this report is computer vision.

As a means for understanding, an abstract framework for computer vision can be described as a pyramid. This can be put into the context of sensing and cognition for UGVs. The basic premise is that there are levels of image understanding, beginning with basic processes on raw data, like image pixels, up to the most abstract reasoning, such as the understanding that a target of interest is present in an observed scene. As a process progresses in stages up towards understanding, there is a reduction in the size of the data set required. This is because groups of data are abstracted into higher levels of understanding. Figure 3 illustrates this perception pyramid notion.

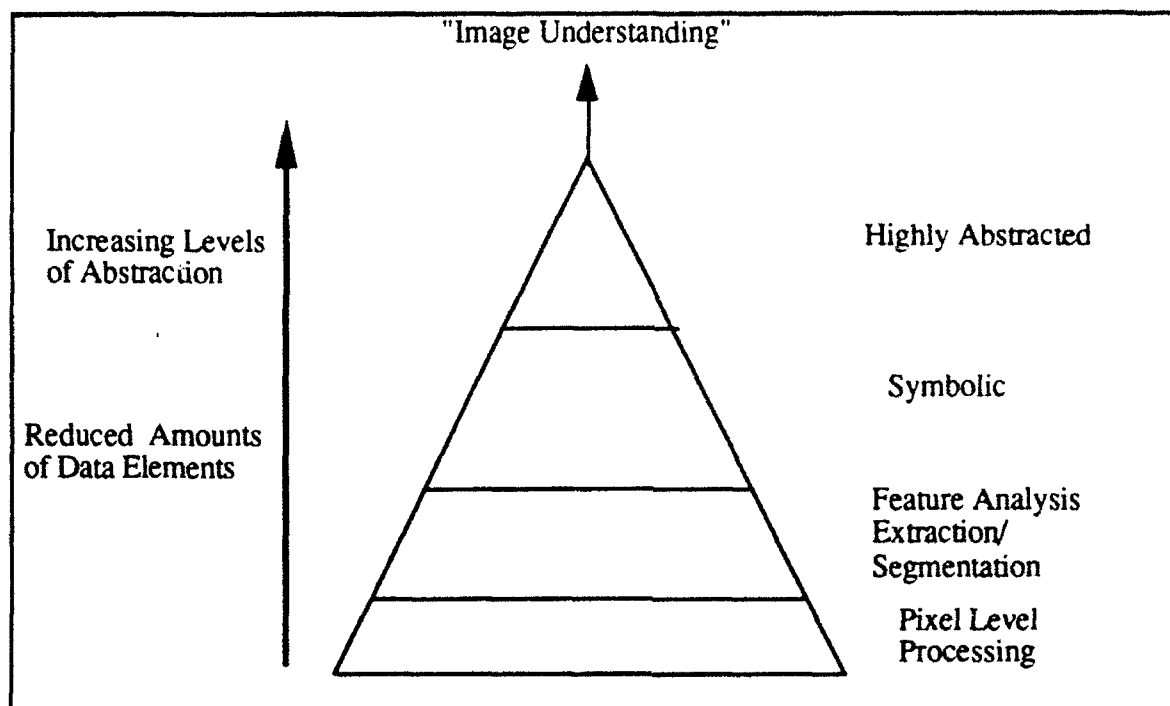


Figure 3. Perception Pyramid Showing Progression of Low Level Data to Higher Level Understanding in Stages.

The pyramidal concept of perception influences ERIM's categorization of algorithms and specialized computing architectures for image understanding. Quality algorithms, and computing hardware, are required at all levels of the pyramid in order to adequately address the perception needs for UGV applications. Specific examples of existing or developing computer vision platforms include iWarp (see section 7.15), ATCURE¹, ALADDIN¹, and IUA (see section 7.6). These architectures provide a capability to increase the throughput at each of these levels of interaction. For instance, iWarp and ATCURE concentrate on lower level pixel processing and feature extraction, whereas the IUA is aimed at automating up to symbolic processing.

Human interaction is also possible and even desirable at the higher levels of perception. Teleoperated vehicles, for instance, require human interaction at the higher levels of "symbolic" processing in order to perceive obstacles and determine desirable paths. The role of perception in the decision process is illustrated in Figure 4.

¹ATCURE and ALADDIN are automatic target recognition computing systems currently under development by the U.S. Army.

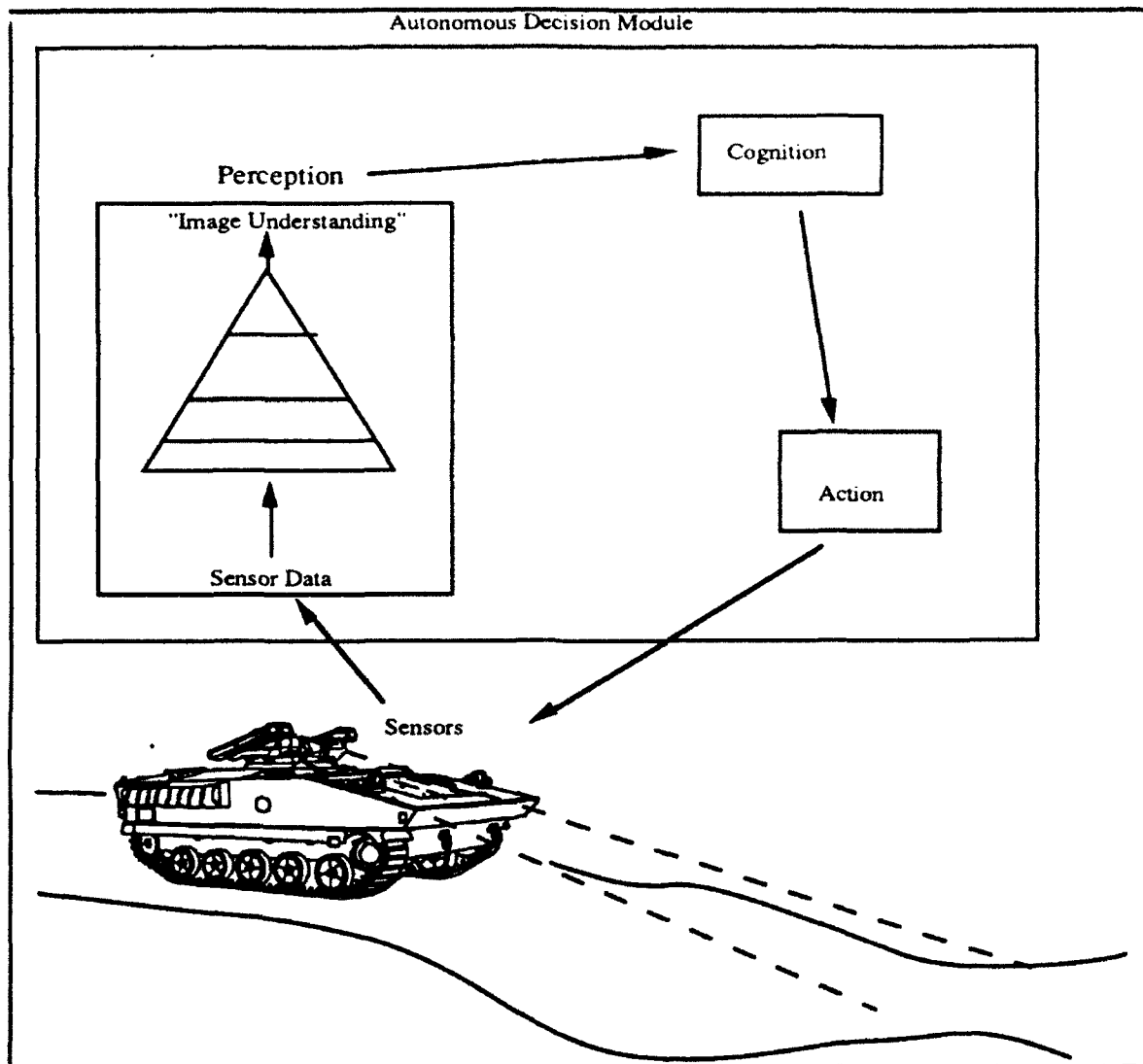


Figure 4. Role of Perception in Autonomous Decision Cycle

Cognition, another focus of this study, can also be understood in more detail in terms of two major elements:

- 1) World and environment modeling.
- 2) An intelligent agent that operates on these models in order to plan and direct action.

It is understood in the robotics community that a reasoning machine must have two kinds of models on which to operate: World models and environment models.

Many versions of world models have been propounded. They are described in terms of map coordinates, analyzed features, and prominent landmarks. World models are typically known *a priori* before a UGV begins a mission. Typical scenarios call for periodic updates from on-board sensors or periodic communication with an outside source.

Environment models are different than world models both in their horizons and in time scale. Environment models are typically not known *a priori*, or are only sketchily known. Environment models allow for local path planning and reactive movement to locally encountered threats and obstacles (e.g., how do I move around this rock? or how do I avoid this enemy armored vehicle?). Environment models include simple occupancy² maps up to complex CAD/CAM descriptions of the local environment.

Figure 5 illustrates the main elements of cognition.

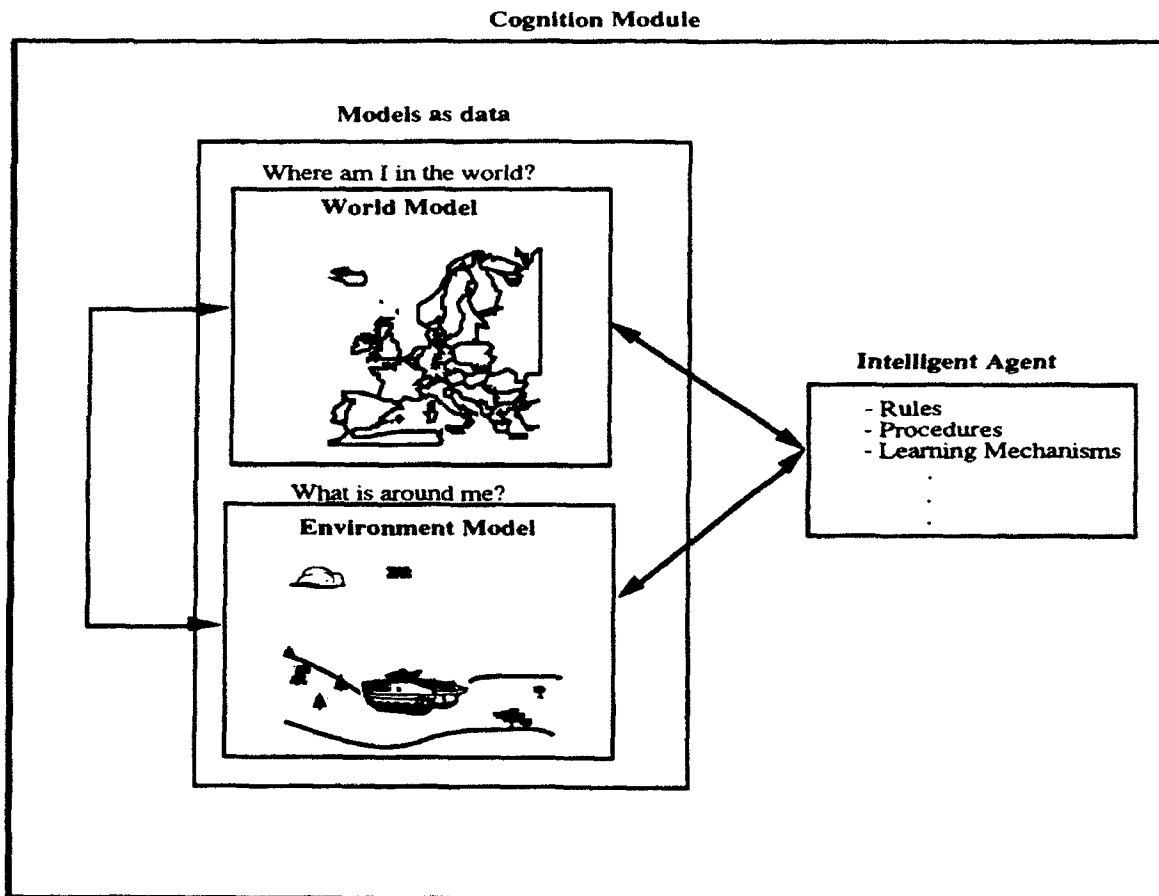


Figure 5. Elements of Cognition

The data elements for the models required in the cognition module are provided, not by the sensors, but by the perception module after raw sensor data have been processed. Naturally, this means that there is a tight coupling of methods and procedures from the perception module and the modeling portion of the cognition module. Figure 6 illustrates

²Occupancy maps divide the world into simple cubes and flag whether a cube is partially occupied by an object.

the place of the cognition module in the decision cycle, and how perception feeds the modeling elements.

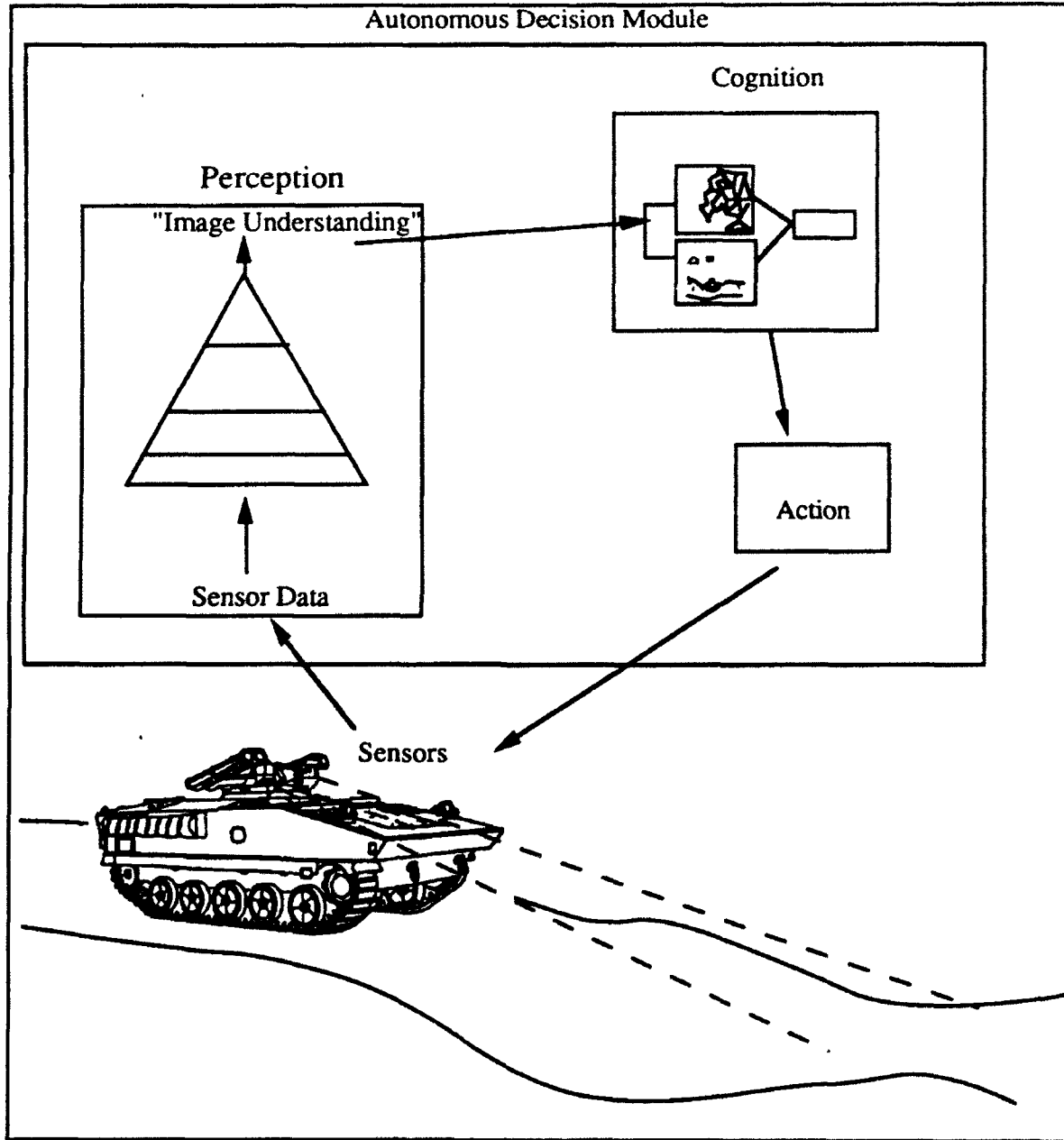


Figure 6. Coupling of Perception and Cognition Through Model Elements

The intent of this exposition was to provide a top-level understanding of the entire process of autonomous vehicle navigation and employment. Although it is still somewhat abstract, Figure 6 provides a basis for understanding technologies that could solve some of the needs in the process. For instance, sensing for perception can be accomplished by either 3D active ranging or 3D passive stereo. The need for 3D sensing is dictated by the need in

the environment model for 3D information, particularly for local path planning and driving execution, thus showing the linkage that dictates requirements on the sensor.

2.3 TECHNOLOGIES WITHIN FUNCTIONALITIES FOR VARIOUS LEVELS OF CONTROL

The previous section has expounded on the entire process of autonomous control from an abstract point of view. The purpose of this section is to identify specific functionalities and technologies that could potentially perform these needed functions. This will then provide an infrastructure of understanding the importance of specific technologies are to the UGV navigation process.

The main uses of military autonomous UGVs will be in support of hazardous operations, including providing reconnaissance and surveillance or remote target acquisition. Neither of these applications will emphasize precise or delicate movement of effector units, which is a major area of development in industrial robotics, fire control, or explosive ordinance handling. The analysis of technologies required for autonomous UGVs are unique in their emphasis. This fact is reflected in the following discussion regarding functionalities and technologies required to achieve autonomous operation in ground combat.

A careful study of needed technologies for various levels of autonomy has led the authors to derive the list of functionalities presented below. The definition of functionality here means that the needed function must be performed, however, in many cases, there exists more than one technology that could potentially meet that functionality. A good example is 3D sensing: either passive stereo, active laser, MMW radar scanning, or an array of simple sonar ranging devices can provide three dimensional information for navigation.

Listed below is a complete list of functionalities that the authors have derived from existing technology. Functionalities marked with an * are those that are the focus of this study.

Perception Functionalities

- Navigation Sensors *
- Sensor Preprocessing *
- Navigation Perception Algorithms*
- Computer Vision Architectures *

Cognition Functionalities

- Navigation Planning *
- World Model *
- Environment Model *

Action Functionalities

- Communications Link*
- Mission Sensors

- Mission Related Perception
- Effectors
- Man Machine Interface
- Vehicle Model
- Integrating Architectures
- Actuators
- Mobility Platforms

What follows are some definitions and examples of what each of these functionalities mean for those which were analyzed in this study.

2.3.1 Definitions of Functionalities

Navigation Sensors

The actual sensing equipment and the associated data. True perception is a combination of sensors and algorithms, which is reflected in these two categories. Naturally, there are some fuzzy boundaries between these definitions; for instance, stereo vision will be included in this category though it naturally relies heavily on intensive computational procedure.

Navigation Perception Algorithms

Once sensed data is collected and processed, the data must be converted into a form that is usable by a human or an intelligent planner. Perception algorithms include generic concepts such as Depth From Focus Blur or Depth from Optical Flow³. Perception, then, is the ability to convert sensor data into a model for use by an intelligent planner (human or machine).

World Model

World models are ways of describing in a global sense where the vehicle is. Latitude and longitude is one way of describing position, position relative to landmarks would be another.

Environment Model

The environment model provides a means of archiving attributes of the local surroundings. Nearby obstacles, roads, holes and hostile threats must be described in greater detail than in the world model. More abstractly, the environment model accounts for the state of the world and is concerned with temporal continuity. This allows for reactive planning to unexpected events and threats.

³ These are technologies for determining range from image characteristics in order to provide 3-dimensional information for planning.

Navigation Planning Algorithms

Navigation planning requires maps of the areas to be traversed for use in planning algorithms. Planning algorithms operate on the data provided from world and environment models. These algorithms represent intelligent automata and as such are replaced by human beings at lower levels of autonomy (telepresence, teleassistance). There are four levels of planning defined in this report: mission planning, path planning, local planning, and obstacle avoidance/reactive planning.

Mission planning requires large areas of the terrain to be surveyed and planned accordingly. It is envisioned that 100's of square kilometers will be included by a mission planner, but at coarser resolution, perhaps 100 meters (DTED Level I). At this level the UGV must be capable of communicating to command and control and other elements of the force structure.

Path planning defines the optimal path for a UGV to take to accomplish a mission. Path planning requires finer detail and a smaller planning horizon than mission planning. It can be envisioned to plan over an area on the order of 10's of square kilometers and perhaps on the order of 30 meter resolution (DTED Level II). Path planning requires communications from the local planner of the details developed therein and a continual updating of the global path plan.

Local planning is envisioned to have a planning horizon within the limit of mission sensors (whether RSTA, NBC, or targeting). Local planning will guide the UGV to the best position within a target area defined by the path planning module. It can be envisioned that resolution requirements might be on the order of 30 cm or better, with a horizon within the limits of the mission sensors. This map for local planning is generated at the UGV by superimposing of local geographic information provided by onboard sensors on geographic map files.

Obstacle avoidance/reactive planning has an even shorter planning horizon, within the space the vehicle has to avoid or react. It is also much more heavily time constrained, and required to react quickly to sensory data provided to it.

Sensor Preprocessing

This includes camera calibration, warping, coordinate registration and other mundane but crucial tasks in preparing sensor data for conversion into world and environment models.

Computer Vision Architectures

This functionality refers to the ability to process both low level (i.e., pixel) and high level (i.e., symbolic) data in a time frame which meets the UGVs operational requirements. Examples of specialized architectures include Image Understanding Architecture or Advanced Target Cueing and Recognition Engine (ATCURE). Other architectures that could be considered include connection machine and other, more general, architectures.

Communications

The planned utilization of UGVs as force multiplication tools will require communication between multiple UGVs and the supervisory command and control network in which they

are embedded. An optimum communication medium must allow non-line-of-sight (NLOS) communication, must be secure, and must be able to support variable degrees of maneuvering ability in both the UGV and the operator control unit.

Additionally, a need for real-time video communication exists primarily at the lower levels of autonomy, namely, telepresence, teleoperation, and teleassistance. Under these types of control, a human operator requires video feedback from the UGV to effectively close the control loop.

2.3.2 Autonomy Versus Functionality

As with any analysis, there are areas of ill-defined functionality, where it is uncertain what degree of functionality is required for a certain level of autonomy. For instance, object recognition and even obstacle avoidance could be useful, even necessary, for a teleoperated vehicle. However, the degree of such functionality would not be as severe as for a fully autonomous vehicle.

The shaded area in Figure 7 corresponds to the functionalities which were studied as part of this report. Question marks (?) indicate that some degree of a particular functionality may be required, whereas closed circles (•) indicate a definite requirement for the level of functionality indicated.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors	•	•	•	•	•	•
Mission Related Perception	•	•	•	•	•	•
Navigation Sensors	•	•	•	•	•	•
Navigation Perception	•	•	•	•	•	•
Navigation Planning	•	•	•	•	•	•
Mission Planning	•	•	•	•	•	•
Path Planning	•	•	•	•	•	•
Local Planning	•	•	•	•	•	•
Reactive Planning/Obstacle Avoidance	•	•	•	•	•	•
World Model	•	•	•	•	•	•
Environment Model	•	•	•	•	•	•
Sensor Preprocessing	•	•	•	•	•	•
Computer Vision Architectures	•	•	•	•	•	•
High Bandwidth Communication	•	•	•	•	•	•
Low Bandwidth Communication	•	•	•	•	•	•
MMI	•	•	•	•	?	?
Vehicle Model	•	•	•	•	•	•
Integrating Architectures	•	•	•	•	•	•
Actuators	•	•	•	•	•	•
Mobility Platforms	•	•	•	•	•	•

Shading indicates focus of present study

Figure 7. Levels of Autonomy Versus Required Functionalities

As stated before, specific technologies already exist or need to be developed in order to satisfy the functionality requirements depicted in Figure 7. A listing of known technology

solutions, either demonstrated or conceptual, will aid in further analyzing the current state of the art in unmanned ground vehicles.

For ease of understanding, technologies have been grouped hierarchically where appropriate. These technologies involve both hardware and software, including sensors, processors, mobility technologies, planning algorithms, communications and man-machine interface issues. Not all technologies listed are required for each level of autonomy. For instance, an elaborate man-machine interface is not required for fully autonomous operation.

Following is a listing of technologies that satisfy, or have in the past satisfied, the required functionalities identified above.

- Navigation Sensors (see section 3.2)

- Passive

- FLIR
 - Low Light Level TV
 - CCD Video
 - Stereo (employing any one of many passive devices)
 - Inertial Guidance

- Active

- 3D active systems (laser operating in the IR for night, or MMW for all weather and night regime)
 - Array of Single Point Sensors (such as small sonars or small IR emitting devices for determining range within a narrow FOV).

- Cooperative

- Global Positioning System (GPS)

- Navigation Perception (see section 3.3)

- Shape from shading
 - Perspective transform
 - Optical flow
 - Depth from focus blur
 - Depth map from stereo
 - Obstacle/Hole detection

- Navigation Planning (see section 3.4)

- Mission Planning

- Neural Net
 - Potential/Gradient Field
 - Landmark Based Navigation

- Case Based Reasoning

- Path Planning

- Neural Net
- Potential/Gradient Field
- Landmark Based Navigation
- Case Based Reasoning

- Local Planning

- Neural Net
- Potential/Gradient Field
- Landmark Based Navigation
- Case Based Reasoning

- Reactive Planning/Obstacle Avoidance

- Neural net
- Gradient Field
- Case Based Reasoning

- World Model (see section 3.5)
 - Cartographic
 - Terrain Models
 - Landmark Model
- Environment Model (see section 3.6)
 - 2D Occupancy Maps
 - 3D Occupancy Maps
 - Hierarchical Occupancy maps
- Sensor Preprocessing (see section 3.7)
 - Image Registration
 - Image Warping
 - Calibration
- Computer Vision Architectures (see section 3.8)
- Communication Link (see section 3.9)
 - Fiber Optic Cable
 - High Bandwidth RF Link
 - SINCGARS (w/ or w/o data compression)
- Mission Sensors

- FLIR
- Low Light Level TV
- Passive Acoustic
- Seismic
- Electronic Support Measures
- Laser Radar
- Radar
- Millimeter Wave (active)
- Mission Related Perception
 - Automatic Target Recognition
 - Automatic Target Cueing
- Man Machine Interface
- Vehicle Model
- Integrating Architectures
 - NIST Robotic Control Structure
 - NOSC Modular Robotic Architecture
 - CMU Blackboard
- Actuators
 - Vehicle
 - Simple Effector (2 or 3 DOF)
 - Manipulator Arms (6 DOF)
- Mobility Platforms
 - Wheeled
 - Legged
 - Tracked

2.4 ASSESSMENT METHODOLOGY

Unlike many other robotics applications, the forecasted requirements that will be placed on unmanned ground vehicles are much different than is expected for an industrial robot. UGVs will have to negotiate difficult terrain that is only partially understood beforehand, and operate in an environment that is neither stable nor controllable. Not least of the uncontrollable aspects of a UGVs environment is the presence of enemies attempting to detect and neutralize it. Therefore covert operation must be a prime requirement. All technology assessments have regarded the need for covert operation as a prime operational consideration.

It is well understood that fielding a practical and usable system requires consideration of many issues outside purely technical concerns. A study such as this would not be complete without consideration of factors that relate to these issues. Technologies that will proficiently solve a given functionality must also be judged on other factors as well, such as those listed below:

- Logistics
- Training
- Maintenance
- Life Cycle Cost
- Mobility
- Deployment
- User Interface
- Survivability
- Effectiveness

In order to assess the technical methods that could solve each functionality, we've taken into account these factors listed above. However, since an assessment is being attempted at a point in time where the technology is very immature, an in-depth study of these system issues is premature. It is nevertheless appropriate to attempt to make comparisons and assessments of even immature technologies, since the choice of a technically simple and supportable technique over a complex technique will influence the ease with which inexpensive and supportable systems will eventually be developed.

Ideal requirements on components of a robotic system entail:

- low technical risk (for yet-to-be-developed technologies)
- high proficiency in solving the problem
- low complexity for ease of maintenance, training, and survivability
- low weight for design flexibility
- low cost, both acquisition and life-cycle

Technical assessment factors include:

- Technical Risk.
- Proficiency.
- Projected logistics requirements.
- Personnel requirements.
- Projected cost.

Consideration of these technical assessment factors was fundamental to the development of the discussion in the next chapter.

3.0 DEVELOPMENT TRENDS OF NEEDED FUNCTIONALITY AND TECHNOLOGIES

This section is intended to condense information about expected maturation of each functionality for each level of autonomy. This condensation is intended to provide a top level, "quick look" view of functionalities and technologies. Supporting information for each matrix element is provided in the text that follows.

3.1 OVERVIEW OF STATE OF THE ART

In order to quickly understand the state of the art compiled in this report, Figure 7 was revised with dates showing when levels of functionality will achieve sufficient maturity for demonstration and validation (DEMVAL). This means that a certain technology that could fulfill a functionality may not be commercial-off-the-shelf (COTS), but is mature enough to be incorporated into the DEMVAL plans of a system acquisition.

It must be understood that such predictions are necessarily difficult and contain many uncertainties. This fact is well understood by the authors. The purpose of developing such predictions is more to understand how functionalities compare with one another more than in developing absolute predictions of when functionalities and technologies are actually going to be available.

Figure 8 illustrates the assessments for technical maturity within each functional area that was a focus of this study. The text following Figure 8 discusses in detail each box and which technologies seem most promising in satisfying the given functionality.

Please note that the dates listed in the boxes in Figure 8 are approximate projections. Their purpose is in understanding relative maturity and trends between functionalities rather than absolute predictions. Further functional satisfaction (that is, technical work) may be required past these dates.

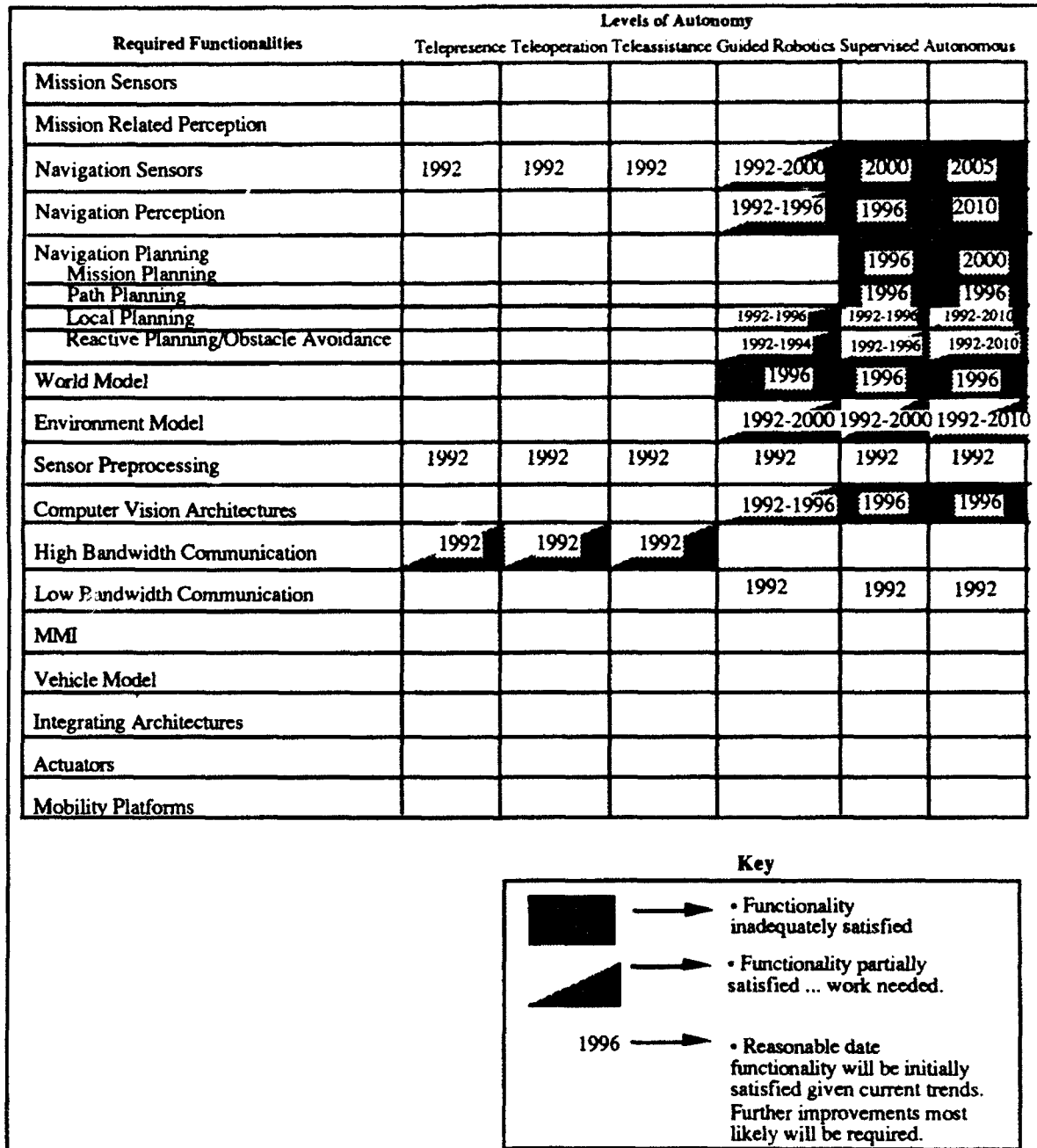


Figure 8. Overview Assessment Functionalities Required for All Levels of Autonomy

What follows is more in-depth description, definitions and justification for each assessment in the matrix in Figure 8. Each functionality will be discussed individually in terms of its maturity versus each level of autonomy.

Each assessment is keyed by functionality, with a subheading for the level of autonomy so that each and every assessment in Figure 8 will have an in depth discussion regarding how the assessments were derived.

3.2 NAVIGATION SENSING

Sensors that adequately provide information for the perception and cognition modules are a critical component in a UGV system. Advancements in electronic sensing, along with advances in computer hardware and software techniques, have made vision possible for UGV applications. Sensors must provide data that allow for timely construction/update of a sufficiently accurate 3D image for determining the local navigation path.

Selection of navigation sensors must consider many factors, including:

- Navigation perception algorithms.
- Military operational requirements.
- Available processors.
- Affordability.

To date, sensing modalities that have been most common in development UGV systems are:

- 3D laser scanners.
- Charge couple device sensors that provide either black-and-white or color two dimensional images (electro-optical or EO sensors).
- The same sensors in multiple arrangements (pairs, triples, ...) to provide passive stereo imagery.

Each of these sensing modalities have their drawbacks. Active scanners like 3D laser scanners violate a basic principle of warfare in that they may give away the position of a unit by alerting an enemy of its presence.

2D electro-optical sensors are limited in the amount of information they can provide, even with the extension to color sensors.

Passive stereo may be limited in its ability to provide accurate enough information at a speed that is consistent with movement in a land warfare scenario. Stereo, in a research setting, can currently provide 1 frame/sec. It is projected that this can be improved to 2-4 frames/sec in the near future. The fundamental limitation to stereo is *correlation* versus *accuracy*. Points in the scene must be correlated in each stereo pair. The more distance between cameras, the more difficult the correlation process. However, the more distance between cameras, the more accurate the depth field is calculated. This fundamental

dichotomy leads one to project there may be a fundamental limitation in stereo capability. To date, stereo provides at least an order of magnitude less accuracy than active laser scanning.

A suggestion to incorporate a multi-tiered sensing system, employing sensors when they are most appropriate is one approach to solving these limitations. For instance, stereo could provide gross information that could key employment of active scanners at selected times and places. However, multiple elements in any system increases the likelihood of failure if any one element fails. The attendant increased system complexity and expense must be carefully considered if such a system is to be employed in harm's way.

For these reasons, we do not believe that current realizations of sensing modalities are adequate for the higher levels of autonomy, and that there is some question that the modalities themselves will ever be fully adequate for navigation sensing for supervised or autonomous vehicles. New modalities should be explored.

Telepresence

By the definition given for telepresence, a high level of human feedback is required for the operator to have the impression that they are at the remote location of the vehicle. In its purest sense, this requires full three dimensional vision, smell, touch and hearing. Although research in this area is ongoing in the form of various "virtual reality" programs in universities, it will be many years before practical, low-cost systems can be fielded for operational use. The justification for this is that only highly structured, specialized applications have allowed the use of any form of telepresence.

However, the narrow definition we have developed here is that we need sensing only for navigation, not necessarily for mission accomplishment. One of the few application areas where telepresence might be useful is explosive ordinance disposal (EOD) and perhaps mine field clearing, again in the mission area rather than navigation. However, DoD currently has plans that provide for this mission capability without resort to more expensive telepresence systems.

Low cost and reliable three dimensional viewing for navigation is currently available and was demonstrated in the TOV program among others. 3D sound is being investigated and implemented by the Armstrong Laboratory of the U. S. Air Force, and will be ready within a few years for implementation in an UGV setting. Therefore, the assessment is that navigation sensing for telepresence in the sense of 3D stereo vision is currently available, 3D sound will soon be available. Also, INS and GPS is useful and is also available currently for global understanding of position for navigation. DEMO I will provide more information on the need for stereo versus flat video for teleoperated/telepresence vehicles.

Teleoperation

Teleoperation, in the navigation area, has a reduced need for sensory data in contrast to telepresence, and by the definitions of this report, flat video would be sufficient. TMAP and the current envisioned TUGV design will employ flat video for navigation purposes. Field testing and user comments will determine the need for transitioning to stereo video for navigation. Day/night capabilities are also available options in terms of either FLIR or Low Light Level TV (LLTV). FLIR offers better all around performance, however is more

expensive than LLLTV. Also, INS and GPS is useful and is also available currently for global understanding of position.

Teleassistance

By the definition in this report, what is required in new sensing capability over teleoperation is the need to detect obstacles and impending collisions independent of the operator. At short ranges, this is possible with acoustic and point IR active sensors. JPL's CARD 2 is an example of a current system with obstacle detection capabilities inherent in the system, though CARD 2 accomplishes this through automatic data extraction of the output from the stereo vision sensor rather than with an enhanced sensor suite. Systems which automatically adjust driving parameters based on the path to be driven immediately ahead of the vehicle are prime examples of teleassisted navigation.

The assessment is that for navigation sensing, this capability now exists for teleassistance.

Guided Robotics

Guided robotics requires that sensors provide data that enable the cognition module to recognize obstacles and that the machine be capable of its own local path planning. Sensors are available for detecting obstacles that then require operator intervention. Holes, ditches and other depressions still pose a significant problem that does not seem to be addressed in current research trends.

Within this report's definition, road following is a constrained version of guided robotics. Speed and resolution still seems to be a problem for use in machine intelligent planners. Road following is becoming available from the research community, as demonstrated by Carnegie Mellon. Off road navigation, or on road navigation under battlefield conditions has yet to be demonstrated in the research community.

To date, the most successful sensor for use in any form of cognitive navigation is the 3D laser sensor (pioneered by ERIM). The other type of sensor used is the range finder stereo system, which is different than the stereo system for use with a human. The range finding stereo provides estimates of range for each pixel in the scene. Current state of the art is a system built by Matthies at JPL which provides a range map of 64 x 60 pixels at 8-bit resolution for each pixel.

Passive stereo imaging is fundamentally less accurate than 3D laser scanners. Road following systems can rely on flat imagery that can be segmented for an understanding of where a road is and where the vehicle should drive itself.

The laser scanner, though more efficient than the stereo solution, does require that an active signal be propagated. In the hostile environments envisioned for frontline UGVs engaged in RSTA, the question of covertness and active scanners is a serious one.

Supervised and Autonomous Robotics

Supervised robotics takes the operator even further out of the loop, to the point where the machine itself is making most decisions related to navigation and movement, allowing user control of multiple units. This requires a sensor capable of assessing traversability. Sensors must be able to make assessments of solidness of ground, detect true obstacles

from false alarms, as well as detect holes and other depressions. To date, these have remained difficult problems to solve.

The two most popular modalities for more autonomous navigation, stereo vision and 3D laser scanning, both have inherent limitations that may not be overcome by further engineering refinements. Stereo vision may always inherently lack speed and/or resolution for adequate perception. 3D laser scanning will always have the potential of compromising covert operations required for primary operations.

The assessment for supervised sensing is the year 2000, for autonomous 2005. These assessments are based on current research trends.

Summary of Findings and Recommendations

For reasons detailed above, we do not believe that current realizations of sensing modalities are adequate for the higher levels of autonomy, and that there is some question that the modalities themselves will ever be fully adequate for navigation sensing for supervised or autonomous vehicles. New modalities should be explored.

As will be stated again in section 6.0, the search for new modalities or the refinement of existing modalities needs to be driven by an overall systems approach that seems to be lacking in current UGV research and development. Each development community (sensor, planning, communications,...) seems to be deriving requirements independent of each other. This seems to be less true in sensors, but is still a significant factor.

Specific examples can be pointed to where an integrated approach is lacking. For instance, traversability assessments are crucial for off-road navigation, even when the human is in direct control of a vehicle from a remote location. An operator or automated driving algorithm will need to know if the patch of ground ahead of the unit is swampy or soft or vegetation covering an impassable ditch or barrier. Current EO and active sensors cannot provide this kind of information, nor have they attempted to. Furthermore, resolution, area coverage and frame rate requirements have not been algorithm driven.

Sensing modalities that could be explored include novel passive stereo, active and passive polarization exploitation, active and passive milli-meter wave, multi-color/multi-wavelength band sensing as well as more system-exotic ideas like multi-sensor fusion for synergistic exploitation of observables.

To date, requirements on the sensor have not been driven by what is required by the cognition module. The issue of requirements on the sensor suite driven by an analysis of what is required by cognition module has not been fully addressed.

3.3 NAVIGATION PERCEPTION

As it has been defined (in 2.3.1), perception does not apply to the first three categories (telepresence, teleoperation, teleassistance), since the human operator is largely providing

the needed interpretation of sensor data⁴. This is why, as will be discussed, three dimensional stereo is so effective when presented to a human operator and is less so when a machine algorithm is required to compute 3D stereo range maps.

The basic problem of perception is the fact that it is a non-invertable problem. A non-invertable problem in this instance means that many conditions can create any one image. Said another way, the world can be inferred many ways from a single image. What is inferred from an image to be a hole may be a mud puddle, a rock or a shiny piece of asphalt, each of which could create exactly the same kind of image. Ways of dealing with non-invertable problems in general are difficult. A complete solution to perception at the highest levels of autonomy will require an understanding of how to treat the non-invertable class of problem.

The current leading candidates of algorithms for perception algorithms are:

- Neural net
- Potential/Gradient Field methods
- Landmark based navigation

Other candidates that have longer realization horizons include:

- Case based reasoning

Neural nets work by attempting to simulate the workings of the inner brain. Neural nets are trained on a set of data (images, or 3D images) and taught what to avoid and perceive in the training set. An advantage of neural nets is their apparent generality. A disadvantage is the inability to trace out WHY a particular decision was made (neural nets have no recovery ability). Another disadvantage is the need to have a large training set available in order to train the algorithm.

Potential/Gradient field systems develop a map-based model that takes into account factors that are important to the unit, such as traversability, lines-of-sight, vegetation or cover and other factors. To date, this has proven to be the most useful algorithm for local path planning.

Landmark based navigation uses local landmarks to allow for fuzzy navigation through terrain that is only partially understood. The definition of a landmark can change from scenario to scenario. This algorithm, admittedly, competes with other kinds of technology, such as GPS and does not provide mission dependent information like Gradient Field does.

Case based reasoning is a new algorithmic approach that takes a lawyer like approach to reasoning. A series of scenarios, or cases, are stored into a memory unit and accessed by a software agent when a new situation arises. Reasoning about what to do next is based on

⁴We assume that obstacle avoidance in teleassisted is by acoustic or point sensor means, therefore the basic capability is in the sensor rather than in the interpretation of sensed data.

the historical experience from the stored cases. Case based reasoning will not be available for practical systems before the turn of the century.

Higher quality sensing systems, that provide dense, quality information (thus reducing the non-invertability of perception) will alleviate the difficulty in developing perception algorithms. This necessarily entails that sensing modalities and perception techniques should be developed hand in hand.

Computer vision is the primary means by which navigation perception will be achieved. Computer vision is still a growing discipline. A general model of computer vision has been generally accepted, in which higher levels of abstraction reduce large amounts of raw pixel data into smaller amounts of generalized knowledge (refer to figure 3). Many techniques have been devised and researched for autonomous vehicle navigation, but robustness is still lacking in the sense that any one technique, or even any combination of techniques, can solve all perception problems required for unaided cross country navigation. Active 3D sensing has proven to be the best overall sensing modality, *primarily because it reduces the burden on the perception algorithms* required to convert the raw sensor data into something that a cognitive module can find useful. This is because it provides more information than passive systems to date, thus reducing the non-invertability of the perception task.

Guided Robotics

Perception for guided robotics has been partially solved, as demonstrated by Carnegie-Mellon's road following successes. Transition into the more general case is required, and may be achievable within the next few years, especially as a result of the DEMO II related efforts as well as the Mars Rover efforts at JPL.

One issue to be considered in this assessment of "solved" perception is the fact that active laser sensing has enabled the success demonstrated. As mentioned earlier, active sensing will not be completely satisfactory for most primary missions envisioned for UGVs.

Supervised Robotics

Perception for the supervised category will be at least partially satisfied given a successful DEMO II, therefore the date 1996 is assessed. It is not expected that a full and satisfactory rating of success can be stated, even given a successful DEMO II, since many issues will undoubtedly remain. However, by 1996, enough enabling technologies should be demonstrated that supervised autonomous vehicles should at least be partially realized.

Autonomous Robotics

Perception algorithms and computing hardware for vehicles that can freely roam unstructured environments will not be ready in the foreseeable future. The requirement for error recovery and rapidly responding to quick, unforeseen events makes this not as likely in the near future. Again, this is in part because of sensors that cannot provide enough information fast enough regarding range, traversability, and other features of the environment to reduce the non-invertability of the basic perception problem.

The assessment, given current research trends in sensors, is that perception for fully autonomous navigation is most likely not ready until the year 2010. Current research

trends in sensors is improved versions of stereo and improved versions of 3D laser scanners.

Summary of Findings and Recommendations

For the higher three categories of autonomy, general comments apply. These are:

- Road following has been demonstrated in a research setting. Within this report, this is considered a limited subset of guided robotics. Given the success demonstrated, road following could be implemented in an advanced system development within a short time.
- Obstacle detection is more developed than detecting holes or depressions (even for teleoperation).
- Fast enough depth map for limited applications from stereo camera pairs should be available by the year 1994, but accuracy and resolution will be limited, requiring powerful perception algorithms to understand the output from such sensor data. Fast enough is on the order of 2-4 hertz. Resolution accuracy is on the order of 1-5 inches of spatial resolution in order to detect obstacles.

It is the author's contention that sensing modalities that can provide consistent and complete information are a major reason for current limitations in robotic functionality. Current perception algorithms are overtaxed and slow, not because of fundamental limitations in and of themselves, but because there is not rich enough information being received from current sensing modalities. If this information were available, programs exploiting higher levels of autonomy could conceivably be entering DEM/VAL by 1996.

Again, like all areas of robotics, an integrated approach to defining requirements and developing systems should greatly affect the development of perception algorithms. A greater appreciation of sensing modalities and their potential information content would positively affect the development of these algorithms.

3.4 NAVIGATION PLANNING

Recall the definitions for the four levels of planning:

Mission planning requires large areas of the terrain to be surveyed and planned accordingly. It is envisioned that 100's of square kilometers will be included by a mission planner, but at coarser spatial resolution, perhaps 100 meters (DTED Level I).

Path planning defines the optimal path for a UGV to take to accomplish a mission, path planning requires finer detail and a smaller planning horizon. It can be envisioned to plan over an area on the order of 10's of square kilometers and perhaps on the order of 30 meter resolution (DTED Level II).

Local planning is envisioned to have a planning horizon within the limit of mission sensors (whether RSTA, NBC, or targeting). Local planning will guide the UGV to the best position within a target area defined by the path planning module. It can be envisioned that resolution requirements might be

on the order of 30cm or better, with a horizon within the limits of the mission sensors.

Obstacle avoidance/reactive planning has an even shorter planning horizon, within the space the vehicle has to avoid or react. It is also much more heavily time constrained, required to plan quickly to sensory data provided to it.

Planning applies only to supervised, guided and autonomous, since it is again assumed that humans will provide planning abilities at the lower levels of autonomy. This functionality has been addressed by artificial intelligence, neural net and other disciplines or combinations of these. The specific techniques that were addressed in this report are:

- Neural Net
- Potential/Gradient Field
- Landmark Based Navigation
- Case Based Reasoning

To date, there has been little actual demonstration of any of these techniques towards planning the route of an unmanned vehicle to traverse unstructured territory. Gradient field techniques appear to hold the most promise. More work has been done on route planning/obstacle avoidance than on higher level mission planning for robotics, hence its relative maturity versus other functionalities. An important point to consider, however, is that there is a large body of mission planning and rehearsal for manned and active units that could be applied to this problem. This has been recognized in the organization and planning for Demo II.

The potential/gradient field method offers the best near term solution for all levels of planning. Gradient field approaches develop a vector map of potentials or gradients that advises the planner how to achieve its objective, no matter where it is on the ground (as opposed to specific route planning that requires a planner to execute a specified route on the ground). Gradient fields can be constructed using all information required to guide an autonomous vehicle, including placement of roads, ground cover, elevation, slope, traversability, field-of-view of opposing enemy units and other factors. More importantly, new information updated continuously from on-board sensors and incoming communications can be used to make real-time decisions. David Payton at Hughes Research Lab, as well as Borenstein and Koren and Jean-Claude LaTombe have studied this field extensively.

Landmark based navigation (as well as qualitative navigation) also shows promise. This technique uses distinctive landmarks or "perceptual events" in order to determine approximate or relative position. However, although useful, position determination actually competes with GPS or INS and may not provide the kind of value decision making the gradient field methods provide. The University of Massachusetts, University of Michigan and ADS have pursued research in this field. Another drawback is that landmarks are heavily context dependent, i.e. a landmark in Saudi Arabia would not be a landmark in Central Europe.

Guided Robotics

Local Planning

To date, the gradient field methods offer the best near term solution to local planning. Neural net technology may prove superior, but is still a new and evolving field. Local planning, being similar in horizon to reactive planning, has evolved further than more abstract levels of path and mission planning. Case based reasoning may prove superior, but is a field in its infancy and cannot be considered for the short term. It is expected that the gradient field work developed for DEMO II will be useful in this category (if demonstrated successfully). Therefore, a reasonable date is 1994-1996, given current research trends. This is especially true in this category since some level of human intervention is still expected.

An example of successful local planning is the road following capabilities demonstrated by CMU's NAVLAB II.

Reactive Planning/Obstacle Avoidance

The assessment is that potential field methods are at a higher level of development than neural nets and that fieldable examples can be produced by 1993. Obstacle avoidance was demonstrated in the ALV program and the CMU NAVLAB currently performs obstacle avoidance. Although improvement can be accomplished, perhaps through neural nets, it can be stated that a partial capability now exists.

Supervised Robotics

Mission Planning

Mission planning in this category will have less severe requirements because of more human interaction supervising the progress of the vehicle. An intelligent planner is expected to be more of an aid to a human operator who will make all final decisions. In this case, the potential field techniques will be very useful in providing advice. In contrast to neural nets, potential field techniques can describe why a decision was made. Neural nets may not be available for mission planning until 1995 and no convincing approaches have been demonstrated for mission planning. Landmark based navigation has been assessed not to be available until 1998 although landmark recognition and assisted navigation techniques are expected to be available by 1995. Since Hughes Research Labs expect to have a version of the potential gradient method available for DEMO II, the date in this category is 1996.

Path Planning

Path planning is expected to be more automated than mission planning at this level of automation, yet the planning horizon and resolution will be similar to the mission planning horizon. The tradeoff is a less difficult problem in terms of goal achievement versus more processing required. A reasonable date for successful automatic path planning is expected to lag human assisted mission planning. 1996 is the assessed date for this category.

Local Planning

To date, the gradient field methods offer the best near term solution to local planning for this level of autonomy. Neural net technology may prove superior, but is still a new and evolving field. Local planning, being similar in planning horizon to reactive planning, has evolved further than more abstract levels of planning. Case based reasoning may prove superior, but is a field in its infancy and cannot be considered for the short term. It is expected that the gradient field work developed for DEMO II will be useful in this category (if demonstrated successfully). Therefore, a reasonable date is 1994-1996, given current research trends. This is especially true in this category since some level of human intervention is still expected.

Again, as in guided robotics, road following is an example of successful local planning.

Reactive Planning/Obstacle Avoidance

The assessment is that potential field methods are at a higher level of development than neural nets and that fieldable examples can be produced by 1993. Obstacle avoidance was demonstrated in the ALV program and the CMU NAVLAB currently performs obstacle avoidance. Although improvement can be accomplished, perhaps through neural nets, it can be stated that a partial capability now exists.

Autonomous Robotics

Mission Planning

The higher level of planning and intelligence required for fully autonomous mission planning makes this category more difficult to predict. It is expected that gradient fields will again be the most likely candidate, however neural nets and especially case based reasoning may be the most efficient techniques at this level. Given such uncertainty, the best prediction is year 2000 (or longer if case based is required).

Path Planning

Comments are the same as under supervised.

Local Planning

Comments are the same as under supervised, except the added requirements for fully autonomous will prolong the full satisfaction of this functionality until the year 2010.

Reactive Planning/Obstacle Avoidance

The assessment is that potential field methods are at a higher level of development than neural net and that fieldable examples can be produced by 1993. Obstacle avoidance was demonstrated in the ALV program and the CMU NAVLAB currently performs obstacle avoidance. Although improvement can be accomplished, perhaps through neural nets, it can be stated that a partial capability now exists.

Improvement required for fully autonomous navigation may not be available before the year 2010.

Summary of Findings and Conclusions

Mission planning for UGV applications has not been addressed as a separate field of study, however it may not need to be, given the great body of work in mission planning as a whole. Undoubtedly subtleties and variations on the main thrust of mission planning will be required for UGVs but, as a whole, the field may well be in hand for the lower levels of autonomy up through supervised.

Autonomous mission planning, as we have defined it, has not been addressed. It is expected that some variant of a gradient field approach will prove useful. However, it will likely be the year 2000 before a level of satisfaction will be achieved.

3.5 WORLD MODEL

World modeling is closely related to mission and path planning, therefore it applies only to the highest levels of autonomy. The most relevant kinds of technologies that apply seem to be available from the Defense Mapping Agency (DMA) in formats like Digital Terrain Elevation Data (DTED), Digital Feature Analysis Data (DFAD) or other products, like Interim Terrain Data (ITD). Landmark models, such as used in Landmark Recognition and Qualitative Navigation, requires context sensitive world models and will require more development before they are available.

The need for world modeling beyond these kinds of representations is still to be determined. Research and development in this area is still new, however DEMO II is slated to deploy mission planning tools that will allow some understanding of how well these kinds of representations will be suited for an automatic, intelligent planner.

It is assessed that, if successful, a suitable world model can be developed by 1996 based on DMA available products.

3.6 ENVIRONMENT MODEL

Environment modeling is more difficult than world modeling, because the cognition module of an autonomous vehicle requires vastly more fine resolution and more kinds of data in order to detect and avoid hazards, threats and obstacles. In guided robotics, this requirement is not severe, becoming more severe for supervised and most severe for autonomous robotics. Existing environment models include 2 and 3D occupancy maps (pixels and voxels⁵), wireframe models, faceted models, complicated CAD/CAM models based on constructive solid geometry techniques and more symbolic representations of the local environment, such as hierarchical representations based on voxel maps.

⁵Voxels are "Volume Elements" and are used to subdivide the world into uniform cubes.

CMU has used simple 2D occupancy maps for obstacle avoidance, University of Michigan has explored 3D occupancy maps (voxels and octrees⁶) as well as CAD/CAM models and symbolic environment representations. To date, the lower level representations of the environment (without resort to symbolic representations), have been demonstrated.

Again, as cannot be stressed enough, there is a tight coupling of the environment model, the perception algorithm which updates the environment model and the planning agent that uses the environment model to guide the actions of the vehicle. In the case of gradient field planning methods, discussed above, the environment model must include estimates of elevation, slope, traversability, obstacles and any other considerations in the environment that must be taken into account during planning. Sensors must be deployed that can sense these qualities of the environment, and a perception algorithm exist that can extract these qualities from the sensed data.

Since there is such a tight coupling between sensing, perception, and planning; development of an appropriate model cannot precede in any real sense the development of perception algorithms (it can for a world model, since on-board perception is not as highly needed for mission planning, which requires a world model).

Guided Robotics

2D occupancy maps have proven useful in simple obstacle avoidance by CMU. 3D occupancy maps are useful in avoiding obstacles and mapping holes and depressions.

Since 2D occupancy maps have been used to date, the assessment is that this functionality is partially met. Development of higher forms of environmental models will be required. 3D voxels or octree methods will be available by 1995 and hierarchical forms will be ready by 1997-2000.

Supervised Robotics

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Autonomous Robotics

2D occupancy maps have proven useful in simple obstacle avoidance by CMU. 3D occupancy maps are useful in avoiding obstacles and mapping holes and depressions.

Since 2D occupancy maps have been used to date, the assessment is that this functionality is partially met. Development of higher forms of environmental models will be required.

⁶Octrees are similar to voxels, but subdivide the world into non-uniform cubes. The data structure used to relate the cubes is an octal tree structure, hence the term octree.

3D voxels or octree methods will be available by 1995 and hierarchical forms will be ready by 1997-2000. However, because of the extraordinary demands on the environment model, refinement of existing models or new models might have to be developed before autonomous navigation can be achieved. The assessment for this level of modeling is the year 2010.

Summary of Findings and Recommendations

Current trends in environmental modeling will solve the problems of the higher levels of autonomy in the projected future. Occupancy maps with information "tagged" inside cells appear to have the brightest future. The greatest challenge will be in the fully autonomous field, since so much information must be encapsulated and be accessed in short periods of time.

3.7 SENSOR PREPROCESSING

Sensor preprocessing, as defined in this report, is the processing and "massaging" of raw sensor data. Artifacts due to lens aberrations, mis-alignment and mis-focus that can be corrected can be handled by sensor preprocessing. This would include image warping, electronic artifacts due to non-uniform detectors and registration as well. Sensor preprocessing, then, applies equally to all levels of autonomy.

Sensor preprocessing can be a significant systems engineering issue when individual systems are designed and fabricated, especially systems that incorporate new sensing modalities. However, no significant research must be accomplished. Sensor preprocessing from a theoretical point of view is not an issue that will hinder UGV development and deployment, as significant as it is from a systems point of view.

3.8 COMPUTER VISION ARCHITECTURES

Specialized computer vision hardware will still be needed in the foreseeable future to accomplish the higher levels of autonomy, notwithstanding the rapid pace with which general purpose computing is increasing in power. The processor must be able to partition its workload of manipulation, RSTA, and effector chores in a way that these are completed in a timely manner. There is a question of whether these tasks can be accomplished concurrently. Since the needed computational capability may not be available in time, it is necessary to address the issue of assigning priorities to situations and actions, e. g. slow down navigational mobility while RSTA is conducted.

Given the lack of robustness in available computer vision techniques, it is predicted that a combination of many computer vision techniques, each tuned to a particular aspect of the problem, will be required. This, along with the sheer volume of computation required in image domains, will require computing power more than that available from general purpose computers.

Recognizing this, DARPA has funded the Image Understanding Architecture (IUA), a joint effort between the University of Massachusetts, Amherst and Hughes Research Laboratory. This project is scheduled to produce a working prototype by 1996.

Guided Robotics

Because of the reduced need for information throughput, especially at the symbolic level, it can be stated that computer vision architectures currently exist for guided robotics. A good example of this assertion is the use of iWarp in CMU's road following NAVLAB. It has been stated by Jon Webb and Jill Crisman of CMU that the iWarp machine is sufficient for autonomous road following.

Extending guided robotics to more general settings will probably require greater computing power than iWarp, especially at the symbolic and knowledge-based levels of abstraction. Hence, the qualification of 1992-1996 and the half shading in this category in Figure 8

Supervised Robotics

The IUA mentioned above is being developed to support DEMO II, which is an example of supervised robotics within the definitions of this report. Since a working prototype is scheduled for 1996, the date listed in this box reflects the projected development of the IUA.

Autonomous Robotics

Although the planning and cognition modules of a fully autonomous vehicle may require specialized architectures of their own, it is speculated by the authors that if the IUA is proven to work well enough for DEMO II, it will also prove sufficient for the computer vision aspects of this level of autonomous robotics. Hence, the date is the same.

3.9 COMMUNICATION

Communication is a fundamentally important UGV component, not only in support of navigation, but also in support of specific mission applications. In the case of specific missions, it is intuitive that to be completely effective, a UGV must be able to communicate the intelligence it has collected and/or the degree of success of its particular mission. The communication requirements associated with UGV mission operations are perceived (by the authors) to be less constrained than those associated with real-time vehicle navigation and control.

The principle driver of navigation-related communication requirements rests primarily at the lower levels of autonomy (i.e., telepresence, teleoperation, and teleassistance). At these levels, a human operator is integrally involved in vehicle control. The amount of human interaction necessary to operate the UGV at these lower levels places significant burdens on the volume, speed, and accuracy capabilities of the communication system. As reflected in Figure 8, these burdens are not necessarily outside the capabilities of existing communication technologies. The difficulty, or challenge, arises from the need to superimpose military operational requirements on the communication equipment. Specific military operational requirements include the following :

- a desire to maintain a low detectability, or signature, of the transmitter.
- the robustness of the system against electronic counter-measures
- the security of information exchange

- the allocation of a suitable communication band
- the timeliness of the transmission
- the ability to transmit and receive with a non-line-of-sight (NLOS) capability.

There are many options to be traded off between communication system capabilities, military operational requirements, and the functional requirements of the UGVs specific mission and operational regime (i.e., level of autonomy). This study focused specifically on the anticipated communication requirements to support the UGV navigation function. General areas of communication technology are summarized with comments on the trade-offs between their capabilities and some of the military operational requirements mentioned previously.

The following paragraphs briefly state the anticipated communication requirements for each of the levels of UGV autonomy defined in this report. In general, the burden on UGV communication equipment, in terms of functionality and operating within military requirements, is inversely related to the levels of autonomy, i.e., communication requirements are least stringent at the highest levels of autonomy. With increasing levels of autonomy there is a reduction in sensor feedback, to the operator, and also the migration of more control functions to the vehicle. Subsequently, as the level of UGV autonomy increases, it will become easier to specify communication equipment which meets a broader set of military operational requirements

Telepresence

Telepresence, by definition, involves a very high, and complex, level of human-UGV interaction in order to simulate operator presence at the remote location. Subsequently, the communication burden imposed by this level of human involvement is itself quite high. It is reasonable to anticipate multi-channel, high bandwidth communication systems will be necessary to accommodate multiple images and sensors (tactile, sound, seismic, etc), as well as high bandwidth control of the platform's mobility and effector capabilities. Continuous communication is required for UGVs operating in this regime.

Two existing communication technologies, fiber optics and wideband radio frequency (RF), currently represent the best options for meeting the communication load of UGVs operating in the telepresence regime. However, both have significant limitations on the UGVs maneuverability (hence, navigability). Specifically, fiber optics requires a physical tether (essentially an umbilical) and wide band RF systems require a clear line-of-sight to exist between the vehicle and the control station.

Teleoperation

A principle difference between telepresence and teleoperation is the reduction of sensory feedback to the operator. Hence, the quantity of transmitted sensory data is reduced and there is also reason to expect that a lower data fidelity may be tolerated. The principle requirement, from a navigation standpoint, is the need to transmit good quality and timely video to support operator control of the platform. There are significant tradeoffs between the update rate of transmitted image frames and the safe speed of forward progress of the UGV. Since the UGV is still entirely operator controlled, it is anticipated that it will be necessary to transmit multiple scenes to support all levels of UGV navigation (i.e., obstacle

avoidance, local navigation, and path planning). Additionally, by definition, communication between the UGV and the operator control station must be continuous.

As mentioned previously, the assessment is that communication technology now exists to facilitate teleoperation. However, significant remaining work involves evaluating how tradeoffs imposed by military operational requirements effect the teleoperation of the UGV. Of particular interest is the tradeoff between data compression technology and the ability of the operator to effectively control the vehicle.

Teleassistance

This level continues the trend in reducing sensing requirements and, hence, communication requirements, required for UGV navigation. While there is a defined distinction from teleoperation requirements, the UGV is still primarily operator controlled, hence the need to provide imagery for operator-assisted navigation still exists. Since the vehicle has some low level navigation capability, a single scene may be sufficient for operator interaction. As with the previous two levels, communication must, necessarily, be continuous. However, it is at this level that data compression technology can begin to make a significant impact on balancing between the capabilities of existing communication equipment and military operational requirements. Since the vehicle has some rudimentary navigation and control capability, the video frame rate might be reduced without a corresponding change in vehicle speed.

Guided Robotics

At this level, a sufficient amount of UGV control remains with the platform such that compromises between existing communication technology and military operational requirements are readily reached. Hence, for this level of autonomy, and those higher, Figure 8 indicates a date of 1992, with no shading. A key difference from lower levels of autonomy is that the need for communication might become intermittent, with no resulting loss in vehicle navigation capability.

Supervised and Autonomous Robotics

The communication requirements to support UGV navigation at these two levels are virtually identical, and hence, for discussion purposes here, have been combined. The principle requirement of continuous communication, which existed at the lower levels, is significantly relaxed at the supervised and autonomous levels. From a navigation standpoint, both vehicles have a capability to operate substantially on their own, hence when communication with the operator station becomes desirable, the UGVs have flexibility for choosing the location (and hence, the direction), as well as the length and timeliness of the transmission.

Technology

The shaded communication areas shown in Figure 8, for, derive from the need for continuous communication between the UGV and the operator control unit (OCU). This need exists at the lower levels of vehicle control, specifically, telepresence, teleoperation, and teleassistance. Under these types of control, a human operator requires good quality and timely video feedback from the remote vehicle to effectively close the navigation control loop. As the control and navigation capabilities are migrated to the vehicle (as

planned for in the higher levels of UGV autonomy), the need for continuous communication becomes more a function of the vehicle's particular mission.

Three existing communication technologies, based on fiber optic, wide-band radio frequency (RF), and narrow-band RF, have been used extensively to transmit video. However, each of these technologies has significant limitations in terms of supporting operator navigation and control of UGVs. Most of the limitations are well recognized by the UGV community and, thus, have led to several RDT&E programs designed to increase the effectiveness and utility of each technology. The following paragraphs identify the recognized limitations of these three technologies, provide a summary of activities designed to address these limitations, and, in some cases, discuss potential options.

Fiber Optic Communication Technology

Most teleoperated UGV programs have used fiber optic technology as the primary means for communicating with the vehicle. Fiber has been used previously in the Fiber Optic Guided Missile (FOG-M) and the Robotic Obstacle Breaching Assault Tank (ROBAT). The advantages of using fiber include high bandwidth, secure (including low detectability), and, to a lesser extent, beyond line-of-sight communications. The major disadvantage is the existence of a physical tether (essentially an umbilical) between the OCU and the UGV. This tether restricts the maneuvering ability of the UGV through certain key types of terrain, such as forests and rivers. The tether also places restrictions on the relocation of the OCU. Operational concerns, such as vulnerability of the tether to damage (possibly caused by other vehicles driving over it) or entanglement, as well as the complexity associated with payout and retrieval, are also valid.

Since the physical tether is a fundamental requirement, virtually all UGV RDT&E activity related to fiber addresses operational concerns. The Naval Ocean Systems Command (NOSC), in collaboration with CECOM, are noted in particular due to their work to ruggedize fiber optic cable, as well as improve deployment and retrieval mechanisms. Additionally, some private sector organizations (e.g., Optelecom) have developed and demonstrated routine (i.e., golfcart) cable deploy and retrieve mechanisms. On other issues, such as river fording, ideas have been suggested, however there is a recognized lack of test data to substantiate them.

The state of the art in fiber optics has reached maturity, as far as the UGV application is concerned. In the near term, there may be requirements for some low level RDT&E investment, associated with operational concerns, however, large new investments in the technology are not warranted. This is based in part on the fact that other research trends are toward higher levels of UGV autonomy which do not necessarily require continuous communication (from the navigation and control standpoint). Additionally, operations at longer distances, including those behind enemy lines, will best be served by alternate, RF-based, technologies.

Wide-Bandwidth RF Communication Technology

Wide-bandwidth RF communication has generally been viewed as providing an important secondary (fiber being the primary) communication link which enables the teleoperator to retrieve the platform or, potentially, continue the mission. Wide-band RF systems are free from physical tethers and have been used to transmit good quality, real-time video. The principle constraint in using wide-band RF is that a clear line-of-sight (LOS) must be

maintained between the transmit and receive antennas. This constraint restricts maneuvering the vehicle through forests, over hills, and behind buildings. However, system concepts have been proposed which use various types of signal relay stations (e.g., Unmanned Air Vehicles, satellites, or even other UGVs) to help alleviate some aspects of this problem.

Additionally, some SBIR activities, which will be part of DEMO I, specifically address simultaneous transmission of multiple video signals and light weight, low cost, autotracking antennas.

A system concept study looking at the utility of a satellite constellation as signal relay stations was performed by the ARMY Missile Command (MICOM). Such an approach is desirable as it reduces the LOS problem and supports the use of Super High Frequencies (SHF) and Extremely High Frequencies (EHF). These spectral regions are not as crowded as lower regions and, thus, frequency allocation for UGV operations may be easier to obtain. However, no Low Earth Orbit (LEO) constellation presently exists which could support UGV operation. Some commercial constellations are planned (e.g., Iridium, by Motorola, for a world-wide cellular capability) which may be applicable, however it is not clear that these would provide 100% communication availability in all potential theaters of interest.

Narrow-Bandwidth Communication Technology

Advances in machine intelligence technology will certainly remove the need for transmitting real time video for operator control of a UGV. However, the need for video communication will probably remain in support of mission-related functions. As with wide bandwidth communication, an optimum narrow bandwidth medium must allow non line-of-sight communication, must be secure, and must be able to support various degrees of maneuvering ability in both the remote vehicle and the operator control unit.

In wide bandwidth RF systems, the LOS dependence is primarily due to the high operating frequencies of these systems. The operating frequency can be reduced in order to achieve better non-LOS performance, however the available bandwidth required to transmit live video does not exist due to the extreme congestion of the frequency spectrum.

A proposed solution involves reducing the bandwidth necessary to transmit a usable video image, through the use of video compression technology. The development of this technology is presently receiving a great deal of worldwide attention and funding because of a broad applicability in areas ranging from high-definition TV (HDTV) through computer video applications to satellite and telephone-line data compression. Video compression RDT&E, in support of UGV operations, has centered on two major areas, technique and human factors.

Several organizations are presently investigating the feasibility of controlling UGVs by means of low data rate, narrow-band, RF links. One alternative is to use a packet-switched radio, such as the single channel, ground/air radio system (SINCGARS). However, SINCGARS, which has a low probability of intercept and a low probability of detection, can only support transmission of 16 kB/s. While this rate may be adequate for command, control, and status, data compression techniques are required to support video transmission. Specifically, in order for a system such as SINCGARS to be effective in this application, the video signal must be compressed, transmitted, and then decompressed. In order to investigate SINCGARS as a viable option for real-time image transmission, DOD

has on-going research efforts directed toward the development of robust video compression techniques.

Another particular technology involves a feedback limited control system (FELICS) which uses selectable tradeoffs between the level of video compression and the bandwidth of the video channel. Specifically, the video may be transmitted via a high-rate wide-band video channel or a very narrow-band channel that restricts the video frame-rate to well under one frame per second. DEMO I will provide more information on the utility of FELICS technology.

Additionally, other efforts are aimed at understanding how much video information must be transmitted for the safe operation of the vehicle. Groups, such as Sandia National Laboratories, have conducted operator tests in an attempt to understand some of these issues.

Summary of Findings and Recommendations

The communication technologies required for military application of UGVs are, for the most part, currently available, hence the projected date of 1992 shown for this functionality in Figure 8. The challenges arise from the superposition of military operational requirements on the UGV communication equipment. These challenges are particularly acute at the lower levels of UGV autonomy which require continuous communication for effective operation (from a navigation standpoint). To reduce the burden which continuous communication imposes at the lower UGV levels, the main thrust of near-term research should be data compression technologies. This thrust should include compression efforts in both data processing and transmission techniques. It is believed that this technology will continue to be useful as the UGV platform evolves to a more intelligent mechanism. The level of support should reflect the fact that this area already enjoys significant worldwide interest and investment. Hence, we recommend that continuing efforts in support of UGV objectives include evaluation of new hardware and software, as they appear, and the RDT&E of component technologies which are specific to UGV needs. We further recommend that the organizations involved in UGV video compression RDT&E be encouraged to communicate and identify synergistic opportunities.

Additionally, technology that supports beyond line-of-sight operation, without a physical tether, needs to be explored further. Examples include the use of satellites, unmanned air vehicles or linked UGVs, as communication relay stations.

4.0 MISSION RELATED FUNCTIONALITIES AND TECHNOLOGIES

The purpose of this section is to make comments and recommendations on technology issues related to mission areas. The major emphasis of this report has been on navigation related technologies. However, in the process of this investigation it became apparent there are several mission issues which have a significant impact on navigation technologies and their utilization.

Potential missions currently envisioned for UGVs include:

- Reconnaissance Surveillance and Target Acquisition
- Logistics
 - Resupply to forward areas
 - Depot management of material
- Security surveillance
- Environmental surveillance (NBC contamination)
- Weapons platform applications

The initial battlefield mission that will be addressed by UGVs is Reconnaissance, Surveillance and Target Acquisition (RSTA). Logistics is also being addressed, but Demo I and Demo II are both initially aimed at RSTA.

An initial emphasis on navigation, communications and RSTA is a sound development strategy, since these functionalities are fundamental to any battlefield mission. Even individual soldiers perform RSTA and need communication as part of their basic war fighting capability; a UGV in a danger zone can do no less. Furthermore, UGVs must be able to move and operate jointly with maneuver forces no matter what basic mission it is assigned.

4.1 RSTA

The issues related to RSTA are the sensor suite and the associated processing required to discriminate targets from a cluttered background. A large body of work in Automatic Target Recognition/Automatic Target Cueing (ATR/ATC) could potentially be applied to this area, once the core functionalities have been satisfactorily addressed. The basic sensors for RSTA will likely be different than sensors for navigation. Thus, the processing algorithms for ATR/ATC will be different but will utilize some of the same techniques.

The major effort being expended in the current DOD program is in platform mobility to move the mission sensors on the battlefield. However, the real interest of the users will be on the data from the mission sensors. This aspect of the problem must be given more attention as we progress to a useable system. Automatic Target Recognition (ATR) and sensors for ATR are a separate specialty and are being worked on by other groups in DOD. It is not desirable to duplicate their efforts. However, we need to give this aspect of the problem enough effort to ensure we select a suite of sensors which will fulfill mission requirements in the demonstration. Harry Diamond Laboratories is addressing this aspect of the problem in Demo I.

The Reconnaissance, Surveillance, and Target Acquisition (RSTA) mission does not require negotiating terrain in itself, only being capable of getting to possibly isolated but specified locations. Therefore a vertical takeoff and landing system to carry sensors and equipment to these locations may also fulfill this mission. This system could get to more isolated locations quicker. Such a system has been developed and demonstrated as a sentinel CL-227 UAV by Indal Technology of Mississauga, Ontario, Canada. One fundamental question that needs to be answered is - What are the tradeoffs between getting the sensors to location in the air versus on the ground. If the objective is to assist in the development of autonomous vehicle technology for commercial highways, DOE, NASA and other military applications, we want to remain on the ground. Also, transition from the first generation teleoperated system is more straight forward with a ground system. Noise and payload are basic questions for airlifted system versus communication necessary for navigation for a ground system. In fact, a small force of small portable sensing systems containing a battery, acoustic sensor, and camera to supplement the larger mobile autonomous sensing systems may be desirable. These sensors could be placed near roads or strategic areas to provide additional surveillance information.

Another major issue that needs to be addressed is cheap, lightweight onboard stabilization of sensors.

4.2 LOGISTICS

Other applications of the technology developed herein include the logistics areas of resupply of forward areas, depot management and convoys of equipment/weapons. These systems utilize some of the technologies developed in the current UGV program, but will also require some additional developments.

Resupply of forward areas requires communications with both the front units and the logistic network. Effector technology for material transfer will be an important issue which is not present in the RSTA mission. Because of the hazardous nature of the environments in which these systems will operate, rapid and/or automatic material transfer while moving will be desirable.

Depot management and material distribution at various levels are another mission for UGVs. This would utilize more capable UGVs than automated warehousing but is based on a similar utilization concept. This would reduce personnel demands and material losses by restricting access to stores. The entire process of material acceptance, handling, storage, security, inventory management and redistribution could be automated. This may require electronic labeling of cartons and active interrogation capability be added to the UGV.

The success of road following demonstrated by CMU should be followed up with some useful and accomplishable Advanced Technology Transition Demonstration that could lead into a fieldable automated road following module system. Convoy supply, in which vehicles can automatically resupply front line troops along specifically defined roads, is one potential application. These systems could be in kit form which would reduce the personnel demands for some logistics applications. There are other transportation or maneuvering applications which could also be satisfied by a road following capability.

4.3 SECURITY AND ENVIRONMENTAL SURVEILLANCE

Security and environmental sensing (SES) requires additional monitoring sensors for detecting threats, concentration of chemical species, and radiation levels. Automating these applications with UGVs both reduces manpower demands and removes humans from hazardous locations. Since this mission is similar to RSTA, only integration of these mission sensors into the UGV should be required. Repetitive patrolling of security perimeters is a logical first application of unmanned ground vehicles.

4.4 WEAPONS PLATFORM APPLICATIONS

Certain weapon platforms are used in a repetitive mode and are hazardous locations as they are natural high priority targets. Utilizing UGV technology for this application has advantages because the vehicle can be designed and built without regard to crew requirements, communication can be automated with command and control, and fire control can be automated while stationary or moving. This will require automated weapon effectors for aiming, loading, and firing in addition to the basic UGV technologies currently in development.

5.0 ONGOING WORK AND INSTITUTIONS ENGAGED IN TECHNOLOGY DEVELOPMENT

The nation's UGV R&D activities are currently focused on three major areas. These are:

- DOD Robotics (UGV) program in support of land warfare,
- DOE Environmental Reclamation and Waste Management Program, and,
- NASA Space Exploration Initiative.

These R&D activities are described briefly below.

5.1 DOD ROBOTICS (UGV) PROGRAM

This program emphasizes the development of those artificial intelligence and robotics technologies which have the best promise as force multiplier to counter the effect of land warfare reductions as well as provide intermediate teleoperated UGV solutions that remove the soldiers from extremely dangerous activities and prepare the forces for future introduction of robotic UGVs. The DOD programs consist of two components: advanced system developments and technology development and demonstrations.

5.1.1 Advanced System Developments

These developments address near and mid-term military operational requirements, with initial operational capabilities in the late 90's. There are five systems currently in advanced development, three which are in full scale advanced development, one in the initial stages of entering advanced development and one in the planning stages. These will be described from the most developed to the more preliminary systems.

5.1.1.1 Remote Ordinance Neutralization Device (ROND)

This system is designed to provide a safe remote explosive ordinance handling and disarming capability. This system when fielded in the late 90s will replace an assemblage of service-specific teleoperated systems that have very limited operational and utilitarian capabilities. This new system will provide EOD personnel the means to secure unexploded ordinance, attach a render safe procedure device/tool, withdraw to a safe area, and fire/function the tool. The ROND platform will separate the EOD operator safely from hazardous accident/incident sites where explosive, chemical, and radiation hazards are present.

The ROND consists of an operator control console, a mobile platform, a closed-circuit color television system, an RF link, a tethered link, a self-supporting power source, and a manipulator consisting of an arm and end effector with common tools. The control console includes an RF transmitter, fiber-optic transceiver, video receiver, television display monitor, power converter, and associated electronics for mobile platform control and telemetry. The mobile platform is equipped with a removable closed-circuit television camera (with ability for both color or low-light black and white) with zoom lens, removable video lighting, fiber-optic and RF communication links, and associated electronics. The

fiber tether enables system commands and sensor data to be passed between the mobile platform and control console when RF communication is not possible or not desired. A lightweight diesel systems will supply power for operational functions. The ROND is operable in all expected weather conditions including rain, snow, sleet, sand, and dust. The platform is designed for low velocity driving in a wide spectrum of operational environments.

5.1.1.2 Rapid Runway Repair (RRR)

The Rapid Runway Repair unmanned ground vehicle is a remotely operated airfield restoration UGV. The system is capable of runway and surface assessment, hole refilling, debris removal and surface preparation.

The Rapid Runway Repair UGV provides a robotic means of executing runway repair and recover including cleanup of unexploded ordinance, and thus alleviates some of the safety and manpower issues associated with RRR. The repair vehicle can perform under post-attack conditions while the remote operators and other airbase personnel remain at a safe distance. Based on preliminary performance tests of a brassboard design, it is estimated that these remotely operated RRR machines working alone will decrease crater repair time by 35 percent compared to manually operated systems.

5.1.1.3 Tactical Unmanned Ground Vehicle (TUGV)

The Tactical Unmanned Ground Vehicle program is a joint Army – Marine Corps project for teleoperational/teleassisted battlefield RSTA.

The long term objective of the TUGV program is to extend the operational capability to perform RSTA-related missions, without introducing limitations that are not present in alternative manned systems. Future TUGVs will allow an operator to control multiple vehicles and oversee several missions. Other TUGV characteristics such as mobility, deployability, and endurance should match or exceed those of comparable manned systems. The program will increase the effectiveness and survivability of combined armed forces by extending the control radius of human presence on the battlefield.

The first generation TUGV will be a teleoperated, lightweight, helicopter transportable, mobile system. Under the control of a safely positioned remote operator, it can be navigated to its position and perform forward observation over prolonged time periods. In achieving forward presence, this system will significantly lessen the exposure of combat soldiers and marines to hazardous and lethal environments. Potential TUGV missions include RSTA with laser designations and weapon targeting; NBC detection and surveillance; and obstacle detection and breaching.

5.1.1.4 Exterior Physical Security (EPS)

This project, currently in the initial phases of starting Advanced System Development is for guided/supervised robotic security surveillance and enforcement at military sites. The Joint Program Office for Physical Security is initiating advanced system development building on technologies developed by Demo I and Sandia. Because of the constrained environment in which this UGV will operate, it has the potential for increased robotization using rote robotic technologies (CARD, Retrance, Retrack, etc.) A major remaining issue is which technologies are affordable.

5.1.1.5 Robotic Countermine (RCM)

This project is currently in early planning to exploit guided/rote robotic technologies for mine detection and clearing. Currently OSD is evaluating technologies available for protecting our maneuvering forces from land mines and looking at both near and far term options. The current emphasis is how we can adapt fielded armored combat vehicles for the countermine mission.

5.1.2 Technology Development and Demonstration

5.1.2.1 Demo I

This activity has been in progress for several years and will culminate with several organizations participating in a performance demonstration scheduled for the last week of April and the first week of May. The objective is to demonstrate the current state of teleoperated and teleassisted robotic technologies to the user community.

Six HMMWVs developed by different laboratories or Commands will be used in the demonstration (one from BRL, one from HDL, one from IST and three from TACOM). They will be operated remotely via RF link but will include a demonstration of a variety of teleassistance technologies such as retrotraverse. Operator control systems (both portable and the multiple vehicle control system) will be part of the evaluations. Various navigation, reconnaissance, surveillance, and targeting sensors and displays are incorporated on the six different vehicles in order to demonstrate their effectiveness on unmanned vehicles in battlefield scenarios.

The principal purpose of Demo I is to mature critical system component technologies for first generation UGVs and demonstrate their readiness for acquisition programs. Based on the results of Demo I, selected technologies will be integrated into the basic STV for the development of a full-up TUGV prototype. The emphasis is on reducing operator workload while enhancing performance of the RSTA mission. Demo I includes products resulting from non-UGV program activities in order to maximize technology transfer to the UGV program. The majority of the hardware and software for Demo I has already been developed and is operational.

As described below, Demo I emphasizes integrated testing and technology maturation demonstration in the five critical technology areas:

- Human Factors/Man-Machine Interface – Operator workload and performance for the teleoperated and supervisory modes of operation.
- Communication – The relative utility of various wide-band communications and low data-rate communication alternatives.
- Navigation – The effects of high and low data rate operations on full-time teleoperated and supervisory control for day and night mobility operations. Automated mobility modes such as retrotraverse, and obstacle detection/avoidance.
- RSTA Mission Package – Mission package performance while the vehicle is stationary.

- Computer Control Architecture – New options for UGV control through integration of teleoperated and limited robotic control modes.

5.1.2.2 Demo II

The program's objective is to develop and mature within five years those navigation technologies which are critical for the system development of supervised autonomous unmanned ground vehicles to meet the needs of the ground forces of the future. Program focus is on exploiting the artificial intelligence advances made by DARPA's science and technology program. The developed navigational technologies will be transitioned to the principal DoD agencies which are responsible for and support the acquisition of unmanned ground vehicles and to industry to establish an R&D base that will support their development.

The purpose of Demo II is to demonstrate those navigation technologies that are critical to evolving UGVs from labor intensive teleoperation to supervised autonomy. These technologies will enable TUGVs to operate in a limited bandwidth, tactical communications environment, by incorporating a cost-effective, semi-autonomous navigation system, which removes the requirement for the UGV operator to maintain continuous control of driving and RSTA functions. Program emphasis is on exploiting emerging hardware and software advances in passive and active sensing, autonomous navigation, and high performance computing and in demonstrating their maturity for acquisition programs of second generation UGVs by 1995.

Demo II is carried out through a four phase demonstration directed approach, successively increasing the complexity of the UGV system and its robotic capabilities. Each phase is executed in two steps. First, the technologies to be demonstrated will be integrated by the participating universities into a breadboard system on a HMMWV at three geographical sites (CMU, U of Mass., and Stanford). After their performance has been validated, the technologies will be transferred to Martin Marietta Corp. for a brassboard system integration.

The systems integrator and major contractor for this activity is Martin Marietta - Denver. They will be responsible for the integration of technologies being developed at several institutions described below. The principal participating organizations and their major areas of activity are as follows:

<u>Organization</u>	<u>Activity</u>
Martin Marietta - Denver	System Integration
Carnegie Mellon University	System Development, Perception, Road Following
Stanford Research Institute	Perception, Stereo Vision Terrain Understanding
NASA Jet Propulsion Laboratory	Perception, Stereo Vision Micro-robots

University of Massachusetts	Perception, Landmark Recognition, IUA
University of Maryland	Perception, Vision-based Navigation and Recognition
ADS	Planning, Mission Planning
Hughes Research Laboratories	Planning, Path Planning, Behavior IUA
University of Michigan	Cooperative Vehicles
Odetics	Sensors
Alliant	Sensors

The activity and responsibility of these groups have just been defined and contracts have been negotiated. Following is a brief summary of the activities in which these organizations participate.

Carnegie Mellon has been very active in the development and demonstration of autonomous vehicles for the past several years. They have operated both Navlab I and Navlab II in several autonomous demonstrations. They have developed perception and road following algorithms which will be incorporated as part of the demonstrations.

Stanford Research Institute is conducting research in the areas of perception and stereo vision. They have been active in developing design curves to define the limits of stereo vision as well as metrics for vision systems. Stereo analysis techniques developed by SRI will be used to provide understanding for practical application of stereo vision.

NASA JPL is active in developing real time stereo vision techniques, perception, and micro-robotics for demonstrating rough terrain navigation. They are also developing obstacle detection techniques and implementing them on a HMMWV capable of operating at 10 mph.

The University of Massachusetts at Amherst are working on perception, landmark recognition and a processor for high speed image analysis (Image Understanding Architecture, IUA). The perception and landmark recognition work is geared to the goal of autonomous navigation. This work is to develop an autonomous, outdoor mobile UGV capable of accomplishing real time mobile robot navigation in a variety of non-trivial outdoor domains. The Image Understanding Architecture prototype development has the objective of developing a three level parallel processing prototype. Other companies working on this project include Hughes and Amerinex Artificial Intelligence (AAI).

ADS is working on path planning and mission planning for Demo II. They are working on case based planning and qualitative navigation. Their planning approach involves storing high level plans for specific conditions, using model based techniques for planning on the fly and using a scheme derived from their work with resource allocation to handle

conflicting goals. Qualitative navigation is a method of path planning using incomplete information of landmarks. They began contract work in December 1991 so they are just beginning to develop their approach and activities for Demo II.

Hughes Research Laboratories is working on vehicle path planning and behavior. Their approach includes making more information available for continuous planning during motion by using gradient field and higher-dimensional representations. They plan to provide arbitration by developing a scheme in which multiple low level behaviors are active in parallel and each rates the desirability of specific actions with respect to that behavior.

In addition, Hughes is doing the hardware for the Image Understanding Architecture. This parallel processor is expected to be ready by mid-1992 and delivered at that time to the other participants in this project (AAI and the University of Massachusetts).

The University of Michigan is working on cooperative techniques for multiple vehicles. In their approach, called partial global planning, local detailed plans are formulated for each vehicle based on local conditions and the mission of the vehicle. These local plans are then abstracted and communicated to the other vehicles in the formation. Thus, communication bandwidth is reduced and commitment to detail is avoided.

Odetics and Alliant are working on 3-D sensors for vehicle navigation. These are active laser ranging systems for navigation.

5.2 DEPARTMENT OF ENERGY

Unmanned ground vehicle research at the Department of Energy is located at Oak Ridge and Sandia National Laboratories. Activity is focused on teleoperations and on mobile robot navigation in confined spaces. The teleoperation research is focused on nuclear fuels processing and the mobility work is for remote vehicle operation for security applications and hazardous material sensing and cleanup. The DoE and DoD programs in this area are interrelated and coordinated (see section 7.8 for more detail).

5.3 NASA-JPL

JPL is conducting research on techniques for real time stereo image registration and perception from stereo vision. Additionally they have developed large and small robots for implementing and testing mobility and navigation. They have developed a six wheeled twenty five hundred pound robot (Robby), a six wheeled fifty two pound robot (Rocky 3) and they are conducting research with MIT on micro robots. Under contract to the U.S. Army Tank-Automotive Command, JPL has developed the Robotic Technology Test Vehicle. This vehicle, and its associated van for remote command and control, allow a human operator to remotely operate the vehicle over a reduced-bandwidth communication channel. This is accomplished by means of Computer-Aided Remote Driving (CARD) technology developed at JPL, where the human operator views static stereo imagery returned from the vehicle and plans a safe path for the vehicle to follow as far ahead as can be seen (see section 7.10 for more detail).

6.0 FINDINGS AND RECOMMENDATIONS

This study was a review and analysis of research and development ongoing and required for autonomous ground vehicle navigation, and this section contains a summary of observations from this study and issues for consideration and analysis. The projects ongoing at DOE and NASA are synergistic and coordinated with DOD so duplication of effort is not a concern. Also there are no glaring deficiencies in the coverage of technologies required for autonomous navigation. However, robustness and time to develop are concerns with some of the technologies as described in sections 6.1 and 6.2. General findings and recommendations are included in 6.1 through 6.4 and specific recommendations are included in 6.5.

6.1 TERRAIN TRAVERSABILITY

Demo II is addressing perception planning at several levels, sensors for navigation, algorithms for obstacle avoidance, and processors required for real time control. A real problem in autonomous navigation in the battlefield area is traversability of unknown areas (i.e., how solid is the ground?, how deep are the holes?, how steep is the slope?, etc). These problems need to be addressed before selection of the sensor-processor suite for navigation in order to ensure the ones selected have the required capability. Traversability of areas that have not been seen previously by the local force structure is very difficult and may require either detailed premapping of the area of operation by remote (airborne or satellite) assets or new sensors capable of detecting ground water content or soil composition. This will become a concern as initial autonomous navigation capabilities are demonstrated and robustness of the capability comes into consideration.

We recommend that a project to specifically address this problem be initiated. We believe this will require a specially designed new sensor but recommend the project include a requirements analysis phase and an options analysis phase before a sensor design and construction phase is initiated.

6.2 INTEGRATED SENSOR-PROCESSING ANALYSIS

To achieve fully autonomous navigation from a scientific viewpoint, integrated research should be pursued more than has been present to date. Automated planning (including obstacle avoidance) is ultimately based on what information is provided from available sensors. Present planning algorithms make use only of what existing modalities provide them. Some sense of the reverse must or should occur. Currently, no sensor research is planned based on the information needs of planning algorithms. This may lead to a situation where the most optimum approach is not followed. In any sensor-processing application, there is always a fundamental trade-off between capabilities (smarts) in the sensor and capability (smarts) in the processing algorithms and processor. This tradeoff needs to be very carefully examined for the battlefield autonomous navigation application.

A new approach to development would be to compile a list of needed environmental qualities (such as traversability, detecting holes and depressions, vegetation, range maps, ...), determine if existing sensing modalities can provide this information and make recommendations regarding new modalities if such are required.

6.3 MULTIPLE APPROACHES

The DEMO II project will address stereo vision and 3-D range finding for navigation sensing, several planning and obstacle avoidance approaches, and iWarp and IUA for the processor. Multiple approaches help reduce risk and ensure success in a research project. However, there is a desire on the part of the users not to accept the vulnerability of active systems in a hostile environment. The tradeoff between vulnerability for active systems and complexity, range, and accuracy for stereo systems have many implications in cost, logistics, reliability, and other implementation issues. We need to be certain we consider these multiple factors in the selection process between multiple approaches and not select approaches based solely on maturity of development. We recommend this question be addressed now to ensure we really have the options we are pursuing.

6.4 UGV ACQUISITION STRATEGY

The concept of introducing a sequence of a small quantity of teleoperated vehicles into the force structure and gradually providing increased autonomous capability is excellent. It would not be possible to suddenly introduce an autonomous vehicle into the force. Introducing teleoperated vehicles will allow their integration into the command structure and the forces to become familiar with the potential utility of such a system. They will also be able to provide valuable feedback to developers of the next generation designs.

6.5 FUNCTIONAL DEVELOPMENT STATUS

The findings and recommendations regarding the state of development of the various functionalities needed for autonomous navigation are presented by function in this section.

6.5.1 Navigation Sensing

Current capabilities of sensing modalities are not adequate for the higher levels of autonomy, and there is some question that the modalities themselves will ever be fully adequate for navigation sensing for supervised or autonomous vehicles. New modalities should be explored.

The search for new modalities, or the refinement of existing modalities, needs to be driven by an overall systems approach that seems to be lacking in current UGV research and development. Each development community (sensor, planning, communications,...) seems to be deriving requirements independent of each other. This seems to be less true in sensors, but is still a significant factor.

Specific examples can be pointed to where an integrated approach is lacking. For instance, traversability assessments are crucial for off-road navigation, even when the human is in direct control of a vehicle from a remote location. An operator or automated driving algorithm will need to know if the patch of ground ahead of the unit is swampy or soft or vegetation is covering an impassable ditch or barrier. Current EO and active sensors cannot provide this kind of information, nor have they attempted to. Furthermore, resolution, area coverage and frame rate requirements have not been algorithm driven.

Sensing modalities that could be explored include novel passive stereo, active and passive polarization exploitation, active and passive milli-meter wave, multi-color/multi-wavelength

band sensing as well as more system-exotic ideas like multi-sensor fusion for synergistic exploitation of observables.

To date, requirements on the sensor have not been driven by what is required by the cognition module. The issue of requirements on the sensor suite driven by an analysis of what is required by cognition module has not been fully addressed.

6.5.2 Navigation Perception

Navigation perception is only required for guided, supervised, and autonomous levels of autonomy. The following comments apply to all three levels.

- Road following has been demonstrated in a research setting. Within this report, this is considered a limited subset of guided robotics. Given the success demonstrated, road following could be implemented in an advanced system development within a short time.
- Obstacle detection is more developed than detecting holes or depressions (even for teleoperation).
- Sufficiently fast methods (2-4 Hz) which produce depth maps for limited applications from stereo camera pairs should be available by the year 1994, but accuracy and resolution will be limited, requiring powerful perception algorithms to understand the output from such sensor data. Resolution accuracy is on the order of 1-5 inches of spatial resolution in order to detect obstacles.

Sensing modalities that can provide consistent and complete information are a major reason for current limitations in robotic functionality. Current perception algorithms are overtaxed and slow, not because of fundamental limitations in and of themselves, but because there is not rich enough information being received from current sensing modalities. If this information were available, the problems could conceivably be entering DEM/VAL by 1996.

Again, like all areas of robotics, an integrated approach to defining requirements and developing systems should greatly affect the development of perception algorithms. A greater appreciation of sensing modalities and their potential information content would positively affect the development of these algorithms.

6.5.3 Navigation Planning

Autonomous planning applies to the higher levels of autonomy (guided, supervised, and autonomous). Path planning, local planning, and reactive planning/obstacle avoidance are all being researched and several approaches are being developed (see section 3.4). It is expected these approaches will yield significant results by 1996.

Mission planning for UGV applications has not been addressed as a separate field of study, however it may not need to be, given the great body of work in mission planning as a whole. Undoubtedly subtleties and variations on the main thrust of mission planning will be required for UGVs, but as a whole, the field may well be in hand for the lower levels of autonomy up through supervised.

Autonomous mission planning, as we have defined it, has not been addressed. It is expected that some variant of a gradient field approach will prove useful. However, it will likely be the year 2000 before an acceptable level of satisfaction will be achieved.

6.5 1 World and Environment Modeling

World modeling applies only to the higher levels of autonomy and modeling based on Defense Mapping Agency (DMA) products is expected to be developed by 1996. Environment models are more difficult than world models and are required for some types of teleassistance in addition to guided, supervised, and autonomous levels of autonomy.

Current trends in environmental modeling will solve the problems of the higher levels of autonomy in the projected future. Occupancy maps with information "tagged" inside cells appear to have the brightest future. The greatest challenge will be in the fully autonomous field, since so much information must be encapsulated and be accessed in short periods of time.

6.5.5 Communications

The communication technologies required for military application of UGVs are, for the most part, currently available, hence the projected date of 1992 shown for this functionality in Figure 8. The challenges arise from the superposition of military operational requirements on the UGV communication equipment. These challenges are particularly acute at the lower levels of UGV autonomy which require continuous communication for effective operation (from a navigation standpoint). To reduce the burden which continuous communication imposes at the lower UGV levels, the main thrust of near-term research should be data compression technologies. This thrust should include compression efforts in both data processing and transmission techniques. It is believed that this technology will continue to be useful as the UGV platform evolves to a more intelligent mechanism. The level of support should reflect the fact that this area already enjoys significant worldwide interest and investment. Hence, we recommend that continuing efforts in support of UGV objectives include evaluation of new hardware and software, as they appear, and the RDT&E of component technologies which are specific to UGV needs. We further recommend that the organizations involved in UGV video compression RDT&E be encouraged to communicate and identify synergistic opportunities.

Additionally, technology that supports beyond line-of-sight operation, without a physical tether, needs to be explored further. Examples include the use of satellites, unmanned air vehicles or linked UGVs, as communication relay stations.

**PART II. SUPPORTING DOCUMENTATION: SITE VISITS,
REPORTS, AND LITERATURE SEARCH**

7.0 DOCUMENTATION AND VISIT SUMMARIES

7.1 FMC

The robotic projects we reviewed at FMC are mainly conducted under contract from TACOM. These projects are focused primarily on satisfying the needs of Demo I. FMC is using four HMMWV vehicles for this effort; two from FMC and two from the previous TEAM program. FMC has, in the past, developed the MVCT testbed (Multiple Vehicle Control Testbed), which was derived from the Robotic Command Center, both TACOM programs. FMC is also incorporating JPL's CARD system into the testbed. This effort includes working with ADS to incorporate TeamWorks into their programs. The FMC program manager is Lou McTamane and the government program monitor for FMC's efforts is Bruce Brendell, who resides at TACOM.

FMC has also developed a high speed chip for route planning and a Terrain Analysis Processor for use in the command center. FMC has access to global planning software from a number of contractors through their role as integrator on the Advanced Ground Vehicle Technology program (a program to increase automation of manned combat vehicles) and other programs. FMC developed a communication protocol for use in Demo I which they feel is of general utility for controlling multiple unmanned vehicles.

Other research at FMC includes porting algorithms for recognizing landmarks, extracting road information and understanding ERIM laser scanner images to a 16-node butterfly processor built by BBN, Inc. FMC is also investigating neural net technology for autonomous vehicle vision processing.

Figure 9 illustrates graphically FMC's contributions to UGV functionalities.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception				FMC		
Navigation Planning						
Mission Planning						
Path Planning						
Local Planning						
Reactive Planning/Obstacle Avoidance			FMC	FMC		
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures				FMC		
High Bandwidth Communication						
Low Bandwidth Communication						
MMI		FMC	FMC			
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 9. FMC's Contributions to UGV Functionalities

7.2 STANFORD UNIVERSITY

Funding for UGV related efforts at Stanford University is mainly provided by NASA. Their major activities are investigating methods for control of manipulators on mobile platforms in gravity-free situations. Stanford has demonstrations of capture of a moving object by two arms mounted on a single moving platform. This technology is potentially useful in downstream applications and it may have some relevance to Demo II, if Reconnaissance, Surveillance and Target Acquisition or mine neutralization is performed during motion. The points of contact at Stanford University are Tom Vincent and Bob Cannon.

Figure 10 illustrates graphically the work Stanford is performing against the required functionalities derived in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors				Stanford	Stanford	
Navigation Perception						
Navigation Planning						
Mission Planning						
Path Planning						
Local Planning						
Reactive Planning/Obstacle Avoidance				Stanford	Stanford	
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 10. Stanford's Contributions to Functionalities Checklist Derived From Figure 7

7.3 ADVANCED DECISION SYSTEMS (ADS)

ADS is the second planning contractor for DARPA's Demo II. They plan to pursue two major areas of research:

- 1) A case-based planner.
- 2) qualitative navigation.

In addition, they will look at cooperation among a group of vehicles. A contract for this effort was recently awarded and is managed by Capt. Koetz at TACOM.

ADS is taking a case-based approach to planning, in which high-level plans are stored for specific conditions. They intend to develop model-based techniques for planning while moving. ADS expects to handle conflicting goals by prioritizing actions in a scheme derived from their work with resource allocation.

ADS' qualitative navigation work is published. They are planning to extend it, but have not specified exactly what level of effort would be extended. Briefly, qualitative navigation is a method of path planning using incomplete information of landmarks. Landmarks are either stored or learned during operation and stored.

Cooperation will be implemented at both the Operator Control Unit level (which is outside ADS' scope) and at the vehicle level. ADS is planning to study cooperation with and without explicit communication. They are concerned about coordinating the cooperative planning from the OCU with that on the vehicles.

Figure 11 illustrates graphically the work ADS is performing against the identified technologies required for UGV implementation.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised Autonomous	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception						
Navigation Planning						
Mission Planning					ADS	
Path Planning				ADS	ADS	
Local Planning				ADS	ADS	
Reactive Planning/Obstacle Avoidance				ADS	ADS	
World Model					ADS	
Environment Model				ADS	ADS	
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 11. ADS' Contributions to Functionalities Checklist Derived From Figure 7

7.4 NAVAL POSTGRADUATE SCHOOL

Currently, work at the Naval Postgraduate School is being performed in-house without outside contractual support. The major activities involve developing mobile robots for indoor environments, although they will soon start a new program on an autonomous

underwater swimmer. During ERIM's visit, they discussed work on resolving ambiguities in sonar data of irregularly shaped rooms and structures and demonstrated interesting studies of the algorithm accuracy. They have also developed a new representation of turns and curved paths which minimizes slippage and maintains precise positioning information. This research seems most useful as a source of some specific techniques which might be applied to the outdoor UGV problem. The points of contact at the Naval Postgraduate School are Yutaka Kanayam and Robert McGhee of the Department of Computer Science.

Figure 12 illustrates graphically the relevance of the Naval Postgraduate School's work against UGV functionalities. It should be kept in mind that the environment that these functionalities are applicable to at the Naval Post Graduate School are significantly different than those encountered in unmanned ground vehicle applications.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised Autonomous	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception					NPGS	
Navigation Planning						
Mission Planning						
Path Planning						
Local Planning					NPGS	
Reactive Planning/Obstacle Avoidance					NPGS	
World Model						
Environment Model					NPGS	
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 12. Naval Postgraduate School Contributions to Functionalities Checklist Derived From Figure 7

7.5 HUGHES RESEARCH LABORATORIES

Hughes is one of two principal "planning" contractors for DARPA's Demo II (the other being ADS). The effort will be managed by CAPT Koetz of TACOM, acting as DARPA's agent.

The planning approach to be taken by Hughes on the DARPA program is based on their experience on ALV. Basic technical issues raised by that experience were:

- 1) command arbitration problems, and
- 2) problems introduced by abstraction of plans.

In addition to vehicle planning, Hughes will have tasks for mission pre-planning and a simulation environment.

Hughes plans to address the problem of command arbitration by developing a scheme in which multiple low level behaviors are active in parallel and each rates the desirability of specific actions, such as a turn, with respect to that behavior. By this means, Hughes hopes to maintain consistency of actions with multiple goals, e.g. simultaneously staying on a road and avoiding obstacles.

The problems associated with abstraction of plans is to be addressed by replacing the route-based planning developed for ALV with map-based planning. Hughes is considering ways to make more information than a simple path description available for continuous planning during motion. Possibilities include new representations of map-based data, such as gradient field and higher-dimensional representations. A gradient representation associates a direction of desired motion to a goal with each point in a map and is produced in the same process that would be used to derive a specific path.

In addition to these technical problems, Hughes also has the charter to develop a mission pre-planning system for the Demo II contractors, intended to enable an operator at a control station to lay out a general mission plan for multiple vehicles. The kinds of capability envisioned included 3D display of terrain data, simulation of vehicle movement, and mission rehearsal. A major issue will be the type and quality of data available. The 5m DTED resolution used on ALV may be adequate for terrain data, and the DMA TTD and ITD products may also be adequate. A vehicle model with sufficient detail to include response times and distances will be required for simulation. As part of the pre-planning work, Hughes is exploring heuristic methods for analyzing visibility at locations on the terrain.

Hughes is expected to provide all contractors with a simulation environment in which to conduct experiments.

Figure 13 illustrates which identified functionalities the Hughes effort is contributing towards enhancing from Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception						
Navigation Planning						
Mission Planning					Hughes	
Path Planning				Hughes	Hughes	
Local Planning				Hughes	Hughes	
Reactive Planning/Obstacle Avoidance				Hughes	Hughes	
World Model					Hughes	
Environment Model				Hughes	Hughes	
Sensor Preprocessing						
Computer Vision Architectures					Hughes	
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 13. Hughes Contributions to Functionalities Checklist Derived From Figure 7

7.6 UNIVERSITY OF MASSACHUSETTS, AMHERST

The University of Massachusetts, Amherst is pursuing research geared towards the far term goal of solving the problem of autonomous navigation in terms of its "base" research in machine vision and image understanding. This means that most of the research falls in the category of Perception and Cognition. It should be noted that this group has not aimed at developing technology in sensor phenomenology, but is aimed at processing information gained from available sensors. Its image understanding research is geared towards using flat two dimensional images, stereo pairs and motion cues produced from electro-optical devices. Research at UMass also includes planning for action. The points of contact at UMass are Professor Ed Riseman and Professor Al Hanson.

Two projects in support of DEMO II, both DARPA funded, are being pursued at UMass currently. They are:

- Image Understanding and Intelligent Robot Navigation
- Image Understanding Architecture.

Image Understanding and Intelligent Robot Navigation is a program where TACOM is acting as DARPA's agent. Some particulars of this project are:

- June 1991 to June 1994 period of performance.

- Objective is to demonstrate real-time passive 3-D sensing and navigation in unstructured domains. "An autonomous, outdoor, mobile UGV system will be developed capable of accomplishing real-time mobile robot navigation/driving in a variety of non-trivial/natural outdoor domains with increasing levels of autonomous capability" (SOW of contract).

Image Understanding Architecture Prototype Evaluation and Development. (in conjunction with Hughes Research Lab [hardware] and Amerinex Artificial Intelligence, Inc. [software]) is being contracted through Harry Diamond Lab. Some particulars of this project are:

- Objective is to build one prototype of the Image Understanding Architecture for evaluation of 3 level parallel processing concepts.

Figure 14 illustrates graphically what functionalities UMass Amherst is working on in relation to the required technologies list in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Tele. Assistance	Guided Robotics	Supervised Autonomous	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception				UMass	UMass	
Navigation Planning					UMass	
Mission Planning					UMass	
Path Planning				UMass	UMass	
Local Planning				UMass	UMass	
Reactive Planning/Obstacle Avoidance				UMass	UMass	
World Model					UMass	
Environment Model				UMass	UMass	
Sensor Preprocessing						
Computer Vision Architectures					UMass	
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 14. UMass Department of Computer Science Contributions to Required Technologies Checklist Derived From Figure 7

7.7 ROBOTIC SYSTEMS TECHNOLOGY, INC.

RST is developing the Surrogate Teleoperated Vehicle (STV) for the Tactical Unmanned Ground Vehicle Joint Program Office (TUGV-JPO). The short term objective of the TUGV-JPO is to provide a mobility platform capable of transporting a RSTA package.

Part of the RSTA hardware package is also being developed under this project. The first delivery is programmed for the first quarter of FY 1992.

Some features of the STV project include:

- Use of a commercially available mobility platform
- Modular RSTA package, including a laser designator and a FLIR.
- DC Electric drive option of quiet operation.
- Standardization of architecture (VMEbus and VxWorks development environment for teleoperated TUGV's).
- A GPS receiver for navigation.
- An acoustic detection system with a limited automatic target cueing capability.
- A combined fibre optic and radio communication system.
- A man-portable OCU.

Figure 15 illustrates graphically what functionalities RST is working on in relation to the required technologies list in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised Autonomous	Autonomous
Mission Sensors		RST				
Mission Related Perception						
Navigation Sensors		RST				
Navigation Perception						
Navigation Planning						
Mission Planning						
Path Planning						
Local Planning						
Reactive Planning/Obstacle Avoidance						
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication		RST				
Low Bandwidth Communication						
MMI		RST				
Vehicle Model						
Integrating Architectures		RST	RST			
Actuators						
Mobility Platforms	RST	RST	RST	RST	RST	

**Figure 15. RST Contributions to Required Functionalities Checklist
Derived From Figure 7**

7.8 DEPARTMENT OF ENERGY

The Department of Energy (DOE) research and development activity in robotics is focused at Oak Ridge and Sandia National Laboratories.

Oak Ridge

The Oak Ridge program, consists of two major research areas:

- 1) robotics and teleoperations (focus on telepresence)
- 2) machine intelligence and advanced computer systems group.

The robotics and teleoperations area includes groups working in teleoperation and remote systems, robotic sensors and electronics development and robotic mobility and manipulation. Much of this work focuses on teleoperations for Nuclear Fuel reprocessing and is in the area of mechanisms, dynamics and controls for dexterous manipulation. These aspects of the research are of limited interest to autonomous navigation.

However, the sensors and vision aspects of the work and three-dimensional world model representation and update have direct analogy to the needs for three-dimensional space understanding for autonomous navigation. The machine intelligence and advanced computer systems area includes groups working on planning, reasoning and problem solving. The work on mobile robots, while limited to constrained environments includes several aspects applicable to military autonomous navigation problems.

The activities supported by this group includes world modeling at the University of Florida, obstacle avoidance using sonar and navigation using stereo visible imagery at the University of Michigan, manipulation using tactile and proximity sensors and system integration at the University of Tennessee and manipulation at the University of Texas. The implementation of this work on the mobile robot at Oak Ridge, while confined to an indoor environment, provides some of the fundamental technology applicable to the military unmanned ground vehicle navigation problem. They are also working in a collaborative effort with DOD in the development of data compression algorithms for DEMO I and integrating an in-house composite compression algorithm with MIT's prediction image compression algorithm.

Figure 16 illustrates Oak Ridge National Laboratories contributions to the UGV checklist developed in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleguidance	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors		ORNL	ORNL	ORNL		
Navigation Perception				ORNL		
Navigation Planning						
Mission Planning						
Path Planning				ORNL		
Local Planning				ORNL		
Reactive Planning/Obstacle Avoidance				ORNL		
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication		ORNL	ORNL	ORNL		
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 16. Oak Ridge National Laboratory's Contributions to Required Functionalities Checklist Derived From Figure 7

Sandia

Sandia has been previously involved in two robotic vehicle programs (TMAP and RSV) and is currently involved in a third program (RETRVIR).

TMAP (program complete)

TMAP produced two brassboard vehicles, manufactured by Grumman and Martin. The contact at Sandia is Mr. Bill Caskey, project leader, (505) 844-8835. This activity was funded out of MICOM. Products were transferred from Sandia to the UGV JPO when that office was formed. The TMAP program is complete. Sandia involvement in this program ended when TMAP finished. The Martin vehicle had significantly better overall performance and JPO has reports documenting the vehicles and the test regimens. Martin delivered their vehicle to JPO (Huntsville) where it remains essentially unused except, for infrequent VIP demos of the technology. The Grumman vehicle was never delivered and, at Grumman's request, they retained possession as part of an IR&D effort to improve and market the capability internationally. From a technical perspective, both vehicles were

teleoperated. Navigation was provided by the teleoperator using live TV imagery transmitted back to the remote control site over a fiber link (RF was available as backup). Several ergonomic experiments were conducted in which the reliability of the teleoperator to navigate were tested. These experiments involved steerable cameras, color vs. B&W, and variable bandwidth of the communications channel. Each platform did have a dead reckoning capability to provide the operator with a coarse approximation of map location. The computed map location was updated by the operator based on visual recognition of landmarks in the transmitted imagery. The systems had no proximity sensing capabilities.

Robotic Security Vehicle (Program complete)

Under contract from the Defense Nuclear Agency, Sandia has developed and tested the Robotic Security Vehicle (RSV), a brassboard system to perform automatic navigation of a land vehicle in a structured (i.e., previously mapped) environment. The Sandia contact is Paul R. Klarer, project engineer, (505) 846-2974. The vehicle used was the Jeep Cherokee Mobile Robotics Testbed Vehicle, developed at Sandia. The target application for this project is outdoor site security applications. The target market is storage and warehouse DOD sites which have remote sentry requirements. The status of the program is operational - a capability has been demonstrated with the Jeep. Sandia is planning to port the capabilities to smaller, more cost effective vehicles, more suitable to the target application.

The RSV system uses on-board dead reckoning navigation, derived from a fluxgate and an odometer, to determine position and orientation of the vehicle in real time. That data is combined with periodic updates from an external microwave beacon system to reduce position errors to within reasonable limits. The roads or trails that the system operates on are stored on-board as maps, and these maps define the navigation system's limit of knowledge of its surroundings. The use of an *a priori* map decreases the systems utility for autonomous exploration in unknown territory, but has other advantages in terms of reduced computing, lower power and size requirements. Additionally, the need for favorable lighting is eliminated, except where vision is used as an adjunct to the navigation system. A local obstacle avoidance capability is included and is handled by a separate sensor system, using simple sonic range detection sensors. This results in real time navigation capabilities which are enhanced in terms of vehicle speed and continuous motion capability. A present disadvantage of the system is the inability of the local obstacle avoidance system to detect potholes and the inability to automatically adjust driving velocity.

RETRVIR (Program ongoing)

The program currently in progress is the Remote Telerobotic Vehicle for Intelligent Remediation (RETRVIR). This is a Sandia IR&D program to integrate a sensor-based high dexterity manipulator with a remote-controlled robotic vehicle for characterization and cleanup of hazardous waste sites. The Sandia contacts are Ray Harrigan, Manager of the Intelligent Machine Division, (505) 844-3004 and Chris Wilson, project engineer, (505) 844-5276. This program uses a Honda vehicle which has been modified for remote driving control. It is a teleoperated system and, as such, does not yet have any autonomous navigation or local obstacle avoidance capabilities. Navigation is provided by the teleoperator using live TV imagery transmitted back to the remote control site over a fiber link (RF is available as backup). The system is operational and the focus for near term work is to integrate advanced sensors with the manipulator arm for improving controlled interactions with the environment. Force sensing at the end effector is an area of research in

this project. Future plans call for integration of a local obstacle avoidance system using sonic sensors and a reflexive/ potential field algorithm for real-time obstacle avoidance.

Figure 17 illustrates graphically the areas that DOE is working that are applicable to UGV areas or technology.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors		SNL	SNL			
Navigation Perception						
Navigation Planning		SNL	SNL	SNL	SNL	
Mission Planning						
Path Planning						
Local Planning						
Reactive Planning/Obstacle Avoidance						
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication		SNL	SNL			
Low Bandwidth Communication						
MMI		SNL	SNL			
Vehicle Model						
Integrating Architectures		SNL	SNL			
Actuators						
Mobility Platforms						

Figure 17. Sandia National Laboratory's Contributions to Required Functionalities Checklist Derived From Figure 7

7.9 NAVAL OCEAN SYSTEMS CENTER

7.9.1 Autonomous Sentry

Program sponsored by the Army to assist DoD in developing operational indoor sentry systems. A secondary objective might be to assist the Department of Energy in developing robots for monitoring toxic waste containers. NOSC had previously addressed the problems of an autonomous sentry in an internal project that was viewed as an exercise in developing expertise in robotics systems.

A small sentry robot is equipped with multiple sensors to detect sound, motion, light and other observables. Three alternative schemes for navigation are being pursued:

- 1) Guide path
- 2) Unrestricted path planning on a two-dimensional grid
- 3) Cybermotion virtual path technique.

Navigation planning is accomplished off-line on a PC and final instructions radioed to the robot.

Prototypes have existed since 1988 and demonstrations will continue for the next few years. Continued research will include implementing technique on different platforms.

7.9.2 Teleoperated Vehicle

Demonstration of teleoperation of up to three vehicles, exercises to include live firing. Stripped down HMMWV's were used to demonstrate reconnaissance, surveillance, and target acquisition (RSTA) and munitions firing. One vehicle was used only for RSTA, one vehicle was used only for firing and one was used for both. Fiber optic cables used to pass data to remote operator in OCU with controls like HMMWV.

Successful demonstration at Camp Pendleton in September, 1989. Nine missiles fired with nine bullseyes and vehicle achieved 25 MPH speed.

The products of this program were transferred to the UGV JPO under LCOL Harper.

7.10 NASA AND RELATED RESEARCH

7.10.1 Overview of NASA's Telerobotics Program

NASA initiated the Telerobotics Research Program in 1985. This program was intended to foster the development of telerobotics technology for eventual application in the space program. According to Weisbin and Montermello, NASA's telerobotics program can be divided into three areas:

- Teleoperation - a human directly controls the remote device in real time,
- Robotics - the remote device is preprogrammed, and
- Supervisory Control - the human controller gives high level commands which are decomposed and executed by the machine under human supervision.

In the first three years of the telerobotics program, an emphasis was placed on developing generalized telerobotics capabilities; specific tasks and applications were not drivers of the research. In the last four years, however, the emphasis has changed. Smaller programs with specific requirements were created, thus allowing rapid prototyping of systems so that the strengths and weaknesses of a given approach could be determined quickly. Typically, the time from concept development to deployment in an actual application can be one to two decades. At this point, the Shuttle Remote Manipulator is the only robot with real space experience.

Funding for the Telerobotics Program and related activities has come primarily through the Office of Aeronautics and Space Technology (OAST), which is now known as the Office of Aeronautics Exploration and Technology (OAET), although other offices have funded related research programs as well. University grants are also used to promote research in key component areas. Examples include major universities such as Stanford, Carnegie Mellon, Maryland, and Texas. The Office of Commercial Programs at NASA is increasing industry participation in automation and robotics through its Centers for the Commercial

Development of Space (CCDS). These centers are funded typically through \$1 M base grants that is used as seed funding for joint programs with industry. As an example, the Space Automation and Robotics Center (SpARC) at the Environmental Research Institute of Michigan is involved in autonomous, supervised, guided, and teleoperated robotics. The CCDS's operate differently from other programs in that available (current) technology is utilized to a greater extent and industry participation (both cash and in-kind) is essential. These programs are by definition lower cost and the turn around time from concept to delivery is generally on the order of several years, rather than decades.

The most relevant NASA program to UGVs is the MARS land rover, which will be discussed below. This program has potential for contributing substantial technology research to the UGV program.

7.10.2 Representative Listing of NASA's Telerobotics/Rover Activities

The first part of this section addresses NASA's programs to develop rovers for future Lunar and Mars missions. The second part contains a list of selected programs read from the literature. Research is highlighted that is going on in space and terrestrial telerobotics.

• *Lunar/Mars Rover Programs*

The primary effort to create autonomous robots, or *rovers* for Lunar and Mars missions is taking place at NASA's Jet Propulsion Lab (JPL) and Carnegie Mellon University. Both unmanned and piloted rovers are being developed. The unmanned rovers are intended for survey, exploration, and sampling missions and the piloted rovers are needed for long range transportation on planetary surfaces.

Two types of rovers are currently under investigation, with prototypes of each already being tested. At Carnegie Mellon's Robotics Institute, researchers have built a six-legged, 19 foot tall walking machine called the Ambler (Autonomous Mobile Exploration Robot). Work on the Ambler has progressed since 1987, with its first steps being taken in the laboratory in 1990. The Ambler uses a laser scanner to provide range images for path planning and a Sun computer to provide the processing power. The Ambler is capable of stepping over obstacles 1 m high and maintaining a stable, level platform on 30 degree slopes.

At JPL, researchers have taken a different approach to rover design. A semi-autonomous, wheeled rover prototype called Robby has been developed and is being tested in outdoor terrain. Robby is a six-wheeled, three-body rover. It is approximately 13 feet long, 5 feet wide, 6.5 feet high, and weighs 2500 lbs. With 35 inch diameter wheels, Robby can also climb over 1 m high obstacles. Robby also has a commercial robot arm on its front section for sample collection purposes. The rover has two separate processors: one for perception and planning, and the other for wheel and robot arm control. Robby made its first continuous, semi-autonomous journey over rough terrain in May of 1990. A stereo vision system provided input for obstacle avoidance to supplement a general, pre-planned route. JPL researchers are also developing a computer-aided remote driving (CARD) capability for Robby that allows more human control over the robot. JPL has also developed a test vehicle for the U.S. Army Tank-Automotive Command that takes advantage of the CARD technology. The army test vehicle has a van for remote command and control. An operator in the van can communicate with the test vehicle over a reduced bandwidth communication

channel. Stereo images are transmitted to the operator, who can then plan a safe path for the vehicle.

• ***Space Related***

Structural Assembly

Langley Research Center (LaRC) - in orbit telerobotic assembly of large space vehicles and platforms

Supervisory Control of Telerobotics

LaRC - in support of truss construction, automated housekeeping for Space Station Freedom Lab Module, and telerobotic maintenance of external modules

Supervised Inspection

JPL - routine and unscheduled inspection tasks, such as truss struts

Advanced Teleoperation

JPL - demonstrating/evaluating capabilities for space repair tasks

Exoskeleton Anthropomorphic Telemanipulation

JPL - man-equivalent dexterity of remotely operated hands

Failure Tolerant Manipulator Joint Development

JSC, University of Texas, Austin - fault tolerant architectures

• ***University Research***

Multiple Autonomous Robots

Stanford University (ARL) - precise manipulation of objects in free space

Neutral Buoyancy Research

University of Maryland Space Systems Lab (SSL) - neutral buoyancy simulations of EVA/telerobotic work sites

• ***Terrestrial Robotics***

Emergency Response Robot

JPL - for treating hazardous spill releases

Vacuum Plasma Spray Robot

Marshall Space Flight Center - automating VPS for fabricating space transportation system engine hardware

Tile Inspection and Rewaterproofing

Kennedy Space Center, Carnegie Mellon, Stanford Research Institute, Langley Research Institute - ground processing of space constructions

HEPA Aerial Inspection Robot

Kennedy Space Center - automatic inspection of filters for payload changeout room.

Figure 18 illustrates graphically the functionalities JPL is working against those identified in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors			JPL	JPL	JPL	
Navigation Perception				JPL	JPL	
Navigation Planning				JPL	JPL	
Mission Planning				JPL	JPL	
Path Planning				JPL	JPL	
Local Planning				JPL	JPL	
Reactive Planning/Obstacle Avoidance				JPL	JPL	
World Model						
Environment Model				JPL	JPL	
Sensor Preprocessing	JPL	JPL	JPL	JPL	JPL	
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms	JPL	JPL	JPL	JPL	JPL	JPL

Figure 18. Jet Propulsion Laboratory's Contributions to Required Functionalities Checklist Derived From Figure 7

7.11 NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

NIST is involved in two different technical thrusts, control architectures and optical flow. The principal point of contact was Mr. Richard Quintero. The major effort is in the definition of control architectures for intelligent systems, an effort pioneered by James Albus of NIST.

Another technical effort under development using optical flow for depth understanding. Dr. Tsai Hong is the principal point of contact on this effort.

NIST is part of the DEMO I effort and is providing the expertise in the system integration area for the effort as well as installing the low level actuator package for one of the DEMO I vehicles.

In terms of defining an architecture, NIST has defined the following elements of an intelligent system.

- a. Actuators
- b. Sensors
- c. Sensory processing
- d. World Model
- e. Values
- f. Task decomposition

These elements are combined in an hierarchical fashion in order to reduce the amount of information at higher levels of abstraction and reasoning. This view of an architecture requires that global memory can be accessed by all processes and that scalable, parallel computing is available. This architecture more closely follows the single-instruction-multiple-data (SIMD) paradigm for parallel processing.

Figure 19 illustrates NIST's vision of intelligent control system that they call Robotic Control System (RCS).

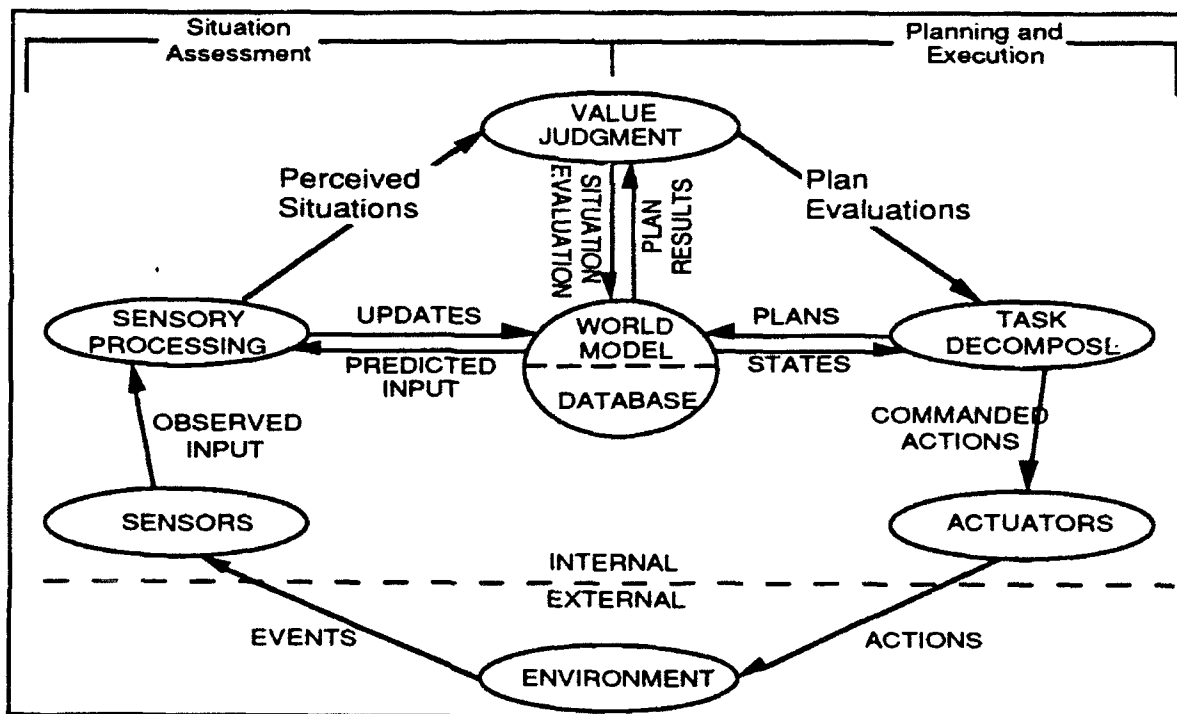


Figure 19. The Elements of Intelligence and the Functional Relationships Between Them

The image flow work is based on the primary assumption of small differences in time (high frame rate) which will allow tracking of individual pixels as they move in space. It was found that this kind of algorithm, being a brute force method, requires tremendous computing power. The current problem is in mapping the algorithm.

The system architecture work is crucially important to adequate development of unmanned ground vehicles. The image flow work, though interesting, probably won't have as much impact in the current study as understanding the architecture work. Figure 20 illustrates graphically the functionalities that the National Institute of Standards and Technology is working against those identified in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception				NIST	NIST	
Navigation Planning						
Mission Planning						
Path Planning						
Local Planning						
Reactive Planning/Obstacle Avoidance						
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures	NIST	NIST	NIST	NIST	NIST	
Actuators						
Mobility Platforms						

Figure 20. National Institute of Standards and Technology's Contributions to Required Functionalities Checklist Derived From Figure 7

7.12 HUMAN ENGINEERING LABORATORY

The principal point of contact was Mr. Tom Haduch. The facilities the Human Engineering Laboratory operates, includes an indoor laboratory for human factors testing related to remotely operating a small vehicle.

Currently, HEL is pursuing three distinct efforts, two as contractual monitors, and one effort as a research center in its own right. They are:

- Man-machine interface research (on-site at Human Engineering Laboratory).
- Low data rate communication research (contract to Oak Ridge National Laboratory).
- High level control architecture (contract to National Institute of Standard and Technology).

Within MMI research, they have identified five distinct areas for further research. They are:

- 1) Controls.
- 2) Vision.
- 3) Information.
- 4) Response.
- 5) Display design.

A further area of research not so easily categorized is communication or display image refresh rate, which is affected by the demands in the five areas above.

According to Haduch, MMI and human factors in general are at an immature stage of development. There is still significant effort in MMI research needed in order to achieve adequate teleoperation. Some of this will be provided from Demo I and the STV evaluations. The state of development of MMI should be reviewed after these activities are completed.

Figure 21 illustrates the technologies that are being researched directly at the Human Engineering Laboratory (HEL), excluding work for which HEL is acting as contract monitor.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised Autonomous	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception						
Navigation Planning						
Mission Planning						
Path Planning						
Local Planning						
Reactive Planning/Obstacle Avoidance						
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI	HEL	HEL	HEL	HEL	HEL	
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 21. U. S. Army Human Engineering Laboratory's Contributions to Required Functionalities Checklist Derived From Figure 7

7.13 UNIVERSITY OF MARYLAND

The principal efforts at the University of Maryland include the exploration of the massively parallel Connection Machine for mission planning algorithms. One of the particular areas

of research was in developing methods to direct a group of vehicles to act cooperatively, using algorithms developed on the Connection Machine. In the past, the University of Maryland had contributed to the Autonomous Land Vehicle program by providing advice to Martin Marietta on road following algorithms.

Also of interest is some exploratory work by Alain Monos of the University of Maryland. Dr. Monos is pursuing visual navigation without resort to a three dimensional environment model, which, if successful, would reduce requirements on sensors; an interesting, if early, research trend. Figure 22 illustrates the contributions of the University of Maryland towards the required functionalities in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors				UMaryland	UMaryland	
Navigation Perception				UMaryland	UMaryland	
Navigation Planning					UMaryland	
Mission Planning						
Path Planning						
Local Planning				UMaryland	UMaryland	
Reactive Planning/Obstacle Avoidance						
World Model						
Environment Model						
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

Figure 22. University of Maryland's Contributions to Required Functionalities Checklist Derived From Figure 7

7.14 UNIVERSITY OF MICHIGAN

The University of Michigan is contributing in the areas of cognitive reasoning, perception, world and environment modeling, obstacle avoidance and multiple agent planning. The principal point of contact is Prof. Ramesh Jain. Some of the more exploratory work that they are pursuing is in how to fuse sensor data from multiple sources. Prof. Jain argues that fusion should occur through assimilation, that is, in the building of the environment

model in the cognition process (refer to Figure 6). In this way, uncertainty introduced by each sensor can be accounted for when updating the environment model.

The University of Michigan is also contributing to DEMO II in the area of multiple agent planning. Dr. Terry Weymouth is the principal point of contact in the DEMO II effort. In order to reduce communication bandwidth and deal constructively with uncertainty, U of Mich has developed a technique called Partial Global Planning (PGP). In this methodology, local detailed plans are formulated for each agent, based on local conditions and the role the agent is supposed to play. These local plans are then abstracted and communicated to the other agents in the formation. In this way, communication bandwidth is reduced, commitment to detail is avoided and meaningless detail is not transmitted.

Figure 23 illustrates the University of Michigan's contributions towards the functionalities in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors						
Navigation Perception				UMich	UMich	
Navigation Planning					UMich*	
Mission Planning						
Path Planning				UMich	UMich	
Local Planning				UMich	UMich	
Reactive Planning/Obstacle Avoidance				UMich	UMich	
World Model					UMich	
Environment Model				UMich	UMich	
Sensor Preprocessing						
Computer Vision Architectures						
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures						
Actuators						
Mobility Platforms						

* In the sense that cooperative contributes to mission planning

Figure 23. University of Michigan's Contributions to Required Functionalities Checklist Derived From Figure 7

7.15 CARNEGIE MELLON UNIVERSITY

The group at Carnegie Mellon has been very active in several aspects of research and demonstration development in autonomous navigation systems. In particular they have been involved in sensor system utilization and evaluation for autonomous navigation, road following algorithm development and demonstration for autonomous navigation, the construction and generation of NAVLAB (an autonomous navigation demonstration system), and the development and utilization of iWarp for autonomous navigation image processing.

Active sensor systems for autonomous navigation evaluated at Carnegie Mellon include active 3-D imaging systems built by ERIM, Odetics and Perceptron. Sensor systems utilized for autonomous navigation include 3-D range imaging, color video, FLIR, INS, and range scanners. demonstrations of road following using these systems on NAVLAB and other vehicles have been developed.

Road following algorithm development has focused on the development and utilization of ALVINN (Autonomous Land Vehicle In a Neural Network). This is a 3-layer back-propagation network designed for the task of road following. Currently ALVINN takes images from a camera and a laser range finder as input and produces as output the direction the vehicle should travel in order to follow the road. ALVINN is a connectionist approach to the navigational task of road following. Specifically, ALVINN is an artificial neural network designed to control the NAVLAB, the Carnegie Mellon autonomous navigation test vehicle.

ALVINN's current architecture consists of a single hidden layer back-propagation network. The input layer is divided into three sets of units: two "retinas" and a single intensity feedback unit. The two retinas correspond to the two forms of sensory input available on the NAVLAB vehicle; video and range information. The first retina, consisting of 30x32 units, receives video camera input from a road scene. The activation level of each unit in this retina is proportional to the intensity in the blue color band of the corresponding patch of the image. The blue band of the color image is used because it provides the highest contrast between the road and the non-road. The second retina, consisting of 8x32 units, receives input from a laser range finder. The activation level of each unit in this retina is proportional to the proximity of the corresponding area in the image. The road intensity feedback unit indicates whether the road is lighter or darker than the non-road in the previous image. Each of these 1217 input units is fully connected to the hidden layer of 29 units, which is in turn fully connected to the output layer.

The output layer consists of 46 units, divided into two groups. The first set of 45 units is a linear representation of the turn curvature along which the vehicle should travel in order to head towards the road center. The middle unit represents the "travel straight ahead" condition while units to the left and right of the center represent successively sharper left and right turns. The network is trained with a desired output vector of all zeros except for a "hill" of activation centered on the unit representing the correct turn curvature, which is the curvature which would bring the vehicle to the road center 7 meters ahead of its current position. More specifically, the desired activation levels for the nine units centered around the correct turn curvature unit are 0.10, 0.32, 0.61, 0.89, 1.00, 0.89, 0.61, 0.32, and 0.10. During testing, the turn curvature dictated by the network is taken to be the curvature represented by the output unit with the highest activation level. The final output unit is a

road intensity feedback unit which indicates whether the road is lighter or darker than the non-road in the current image.

iWarp is the image processor which has been developed by Intel and utilized at Carnegie Mellon for autonomous navigation image processing. iWarp is a programmable systolic array processor of 10 cells, each of which is a processor capable of performing 10 million floating-point operations per second (10 MFLOPS). A 10-cell machine, therefore, has a peak performance of 100 MFLOPS. The Warp machine has three major components -- the Warp array (10 cells), an interface unit (IU), and a host system consisting of three 68020 processors and a Sun Microsystems workstation. The Warp array performs the computation-intensive operations. The IU handles the I/O between the array and the host. The host executes the parts of the application program that are not mapped onto the Warp array and supplies the data to and receives results from the array. The Warp machine is programmed in a special purpose high level language called W2. The language W2 is supported by an optimizing compiler that translates W2 programs into efficient microcode for the Warp cells and the IU, and C code for the host processors. The NAVLAB I vehicle which incorporated these system has been demonstrated doing road following and obstacle avoidance on clearly defined paved roads at speeds of normal traffic. Work is continuing on the evolution of this system to make it more robust and reliable.

In addition, Carnegie Mellon has the NAVLAB II vehicle for demonstration on gravel and dirt roads. NAVLAB II is a modified HMMWV ambulance currently equipped with an ERIM range scanner, video camera, and an inertial navigation system. In the future, a stabilized sensor platform will be mounted on top of the vehicle, housing a Schwartz single scanline laser sensor to replace ERIM's (for faster update rate), a FLIR, GPS, a video camera, and an INS VNAS. The computing system consists of three Sun Sparc2 workstations, 4-7 image buffers, 1.6 GB disk storage, an optical disk, Vx Works real-time operating system software, and 4-axis motion controllers. This equipment is powered by two gas-powered generators with a capacity of 10 KW. In addition, there are four seats, three for researchers and one for an emergency driver.

CMU is initiating some new research in the area of high speed autonomous navigation on rough terrain. CMU is currently building a base-line system to operate at moderate speeds and plans to incrementally increase the high-end operating speeds of the vehicle. The goal is to perform velocity tuning so the vehicle drives at an appropriate speed for the complexity of the terrain and the difficulty of the planned path. A local path planner first plots a course in spatial terms, avoiding obstacles while meeting global path needs. It then formulates an appropriate velocity plan meeting the kinematic and dynamic constraints of the vehicle along the planned path. This system currently operates in simulation mode and will be transported to NAVLAB II.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors			CMU	CMU	CMU	CMU
Navigation Perception				CMU	CMU	CMU
Navigation Planning				CMU	CMU	CMU
Mission Planning						
Path Planning				CMU		CMU
Local Planning				CMU	CMU	CMU
Reactive Planning/Obstacle Avoidance				CMU	CMU	CMU
World Model				CMU		CMU
Environment Model				CMU	CMU	CMU
Sensor Preprocessing				CMU	CMU	CMU
Computer Vision Architectures				CMU	CMU	CMU
High Bandwidth Communication						
Low Bandwidth Communication						
MMI						
Vehicle Model						
Integrating Architectures	CMU	CMU	CMU	CMU	CMU	CMU
Actuators						
Mobility Platforms	CMU	CMU	CMU	CMU	CMU	CMU

Figure 24. Carnegie Mellon University's Contributions to the Functionalities Described in Figure 7

7.16 U. S. ARMY'S TANK AUTOMOTIVE COMMAND

Prior to the Army's shift of UGV related development program responsibility to Micom (FY90), TACOM was one of the key centers of UGV research and development. It is still a major participant in DEMO I and continues to serve as a contracting agent and Army focal point for DEMO II in technical areas of planning and navigation. TACOM has a mix of goals and objectives, ranging from developing fieldable teleoperated systems for deployment in Desert Storm to contributing managerially and technically to the development of autonomous and cooperative unmanned vehicles.

TACOM is active in UGV robotics development from a total system approach, elements of which include navigation, perception, mobility, communication, solder-machine interface and mission function automation. Demo's I and II drive the TACOM plan for Tank-Automotive Robotics. Other projects of interest of historical interest include the Unmanned Ground Vehicle Control Testbed (UGVCT) and the LABCOM Robotically Controlled High Mobility Multipurpose Wheeled Vehicle.

The Unmanned Ground Vehicle Control Testbed, developed by the U.S. Army Tank-Automotive Command, provides a means for evaluating how robotic vehicle units can accomplish combat and combat support missions. Using digital terrain data base products,

automated destination selection and route planning, and computer assisted driving, the testbed can remotely control up to four robotic vehicles simultaneously and can demonstrate six mission capabilities:

- Decoy operation
- Tactical reconnaissance
- Chemical reconnaissance
- Battlefield smoke
- Convoy following, and
- Anti-armor

The testbed is flexible and extensible, facilitating the integration of technologies from diverse sources such as:

- the Small Business Innovative Research program
- the NASA/JPL Computer Aided Remote Driving research effort, and
- DARPA's Autonomous Land Vehicle and Image Understanding Programs.

A more comprehensive list of research and development topics that TACOM has been or is now involved in is:

- route planning
- electronic maps
- teleoperation kits
- convoy controllers
- retrotraverse
- computer aided remote driving (CARD)
- autonomous road following
- obstacle avoidance
- intervehicular cooperation
- autonomous cross country navigation.

Current and planned work areas, projects, and contracts and the status of the projects are listed below. The largest project is the control station under development by FMC. This has totaled \$11 million to date whereas the other projects are \$50K to \$500K. These include the following:

U.S. Army Tank-Automotive Robotics Research Work Units

<u>Objective</u>	<u>Organization</u>	<u>Status</u>
Intelligent Mobility		
Route Planner	KMS Fusion Algorithms	Completed & Transferred ¹
Computer Aided Remote Driving	Jet Propulsion Laboratory	Ongoing & Joint DARPA ¹
Autonomous Mobility	Carnegie Mellon University	Ongoing & DARPA sponsored ²
Outdoor Scene Perception	University of Massachusetts	Ongoing & DARPA sponsored ²
Robotic Convoy	Redzone Incorporation	Phase II approved
Cooperative Mission Planner	ADS Incorporation	Ongoing & Joint DARPA ²
Perception Planning Interaction	Hughes Research Laboratory	FY92 award & DARPA sponsored ²
UGV Mobility Study	Redzone Incorporation	FY92 Phase I SBIR
UGV Platform	Benthos Incorporation	FY92 Phase I SBIR
Remote Control Kit	Redzone Incorporation	FY92 Phase I SBIR Complete
Laser Navigation	Odetics Corporation	Algorithms tested
Soldier Robot Interface		
Multiple & Mobile Control Station	FMC Corporation	Fabrication Completed DEMO I ¹
Multiple Vehicle Control	TII Incorporated	Ongoing Phase II SBIR
Multiple Sensor Control Station	Fietzsch	FY92 FME
Sensors		
Stabilized Platform	Pietzsch	GFP to DARPA Contracts
Multiple Function Sensor	Physical Optics	Ongoing Phase I SBIR
Night Teleoperation Sensor	Baird	HMMWV installed DEMO I ¹
Vision Laboratory	John Griffin	GMI Thesis underway
Communication		
Reduce Bandwidth Microwave & Relieve Tracking Antenna	Microwave Radio Corporation	Delivered Installed VAVCT & Robotic Lab ¹
Electronically Steerable Antenna	TRA	Delivered Robotic Laboratory ¹
Video Compression	Delta Systems	Phase II Complete FY92 ¹
Video Compression	TRC	Phase II Complete FY92 ¹
Intelligent Communication Network	VIASAT	FY92 Phase II SBIR Award
Stacked Antenna Array	Flam & Russel	Phase I Completed Nov 91
Stacked Antenna Array	Atlantic Aerospace	Phase I Completed Nov 91
Mission Automation		
Forward Observer Remote Target Acquisition System	Odetics Corporation	Phase II Fabrication Completed, DEMO I ¹

1 in DEMO I support

2 in DEMO II support

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors						
Mission Related Perception						
Navigation Sensors	TACOM	TACOM	TACOM			
Navigation Perception						
Navigation Planning						
Mission Planning			TACOM	TACOM		
Path Planning			TACOM	TACOM		
Local Planning			TACOM			
Reactive Planning/Obstacle Avoidance			TACOM			
World Model						
Environment Model						
Sensor Preprocessing			TACOM			
Computer Vision Architectures						
High Bandwidth Communication	TACOM	TACOM	TACOM			
Low Bandwidth Communication				TACOM	TACOM	
MMI	TACOM	TACOM	TACOM	TACOM		
Vehicle Model				TACOM	TACOM	
Integrating Architectures						
Actuators	TACOM	TACOM	TACOM	TACOM	TACOM	
Mobility Platforms	TACOM	TACOM	TACOM	TACOM	TACOM	TACOM

Figure 25. TACOM's Contributions Towards the Functionalities Defined in Figure 7

7.17 MARTIN MARIETTA

Martin Marietta has the systems integration contract for Demo II. They plan to begin work on this \$24 million dollar program in January 1992. Martin's previous major activity lies in the development and demonstration of the Autonomous Land Vehicle (ALV) in 1985-88. Since that time they have been funded largely by internal studies with the Baltimore group doing some human interface activities in cooperation with Human Engineering Laboratory.

Martin Marietta has been instrumental in the development of autonomous navigation through their development of the Autonomous Land Vehicle (ALVIN) at Martin Marietta Denver Aerospace. Alvin is a mobile laboratory designed for demonstrating the state-of-the-art in a range of machine intelligence technologies, including computer vision, autonomous navigation, and intelligent planning and reasoning.

The ALV mobile robot performed its first public road-following demonstration in May 1985. The basic perception sensing system was developed to locate roads in video imagery and send three dimensional road centerpoints to Alvin's navigation system. Since that first

demonstration, the perception sensing system has matured into a more general framework for mobile robot vision, incorporating both video and range sensors and extending its road-following capabilities to include obstacle detection and avoidance. A second public demonstration in June 1986 showed the improved road-following ability of the system, allowing the ALV to travel a distance of 4.5 km at speeds up to 10 km/hr, handle variations in road surface and navigate a sharp, almost hairpin, curve. In October 1986, the initial obstacle avoidance capabilities were demonstrated, as Alvin maneuvered around obstacles while remaining on the road at a speed of 3.5 km/hr, and vehicle speeds up to 20 km/hr were demonstrated on an obstacle-free portion of road.

Alvin is an all-terrain vehicle with eight-wheel drive, diesel-powered, and hydrostatically driven, with a fiberglass shell to protect the interior from dust and inclement weather and to insulate the equipment inside. The ALV hosts a number of sensors. A Land Navigation System (LNS) provides position and heading information. The primary vision sensor is a color video CCD camera, mounted on a pan/tilt unit that is under the direct control of the vision subsystem. The other vision sensor is a laser range scanner which determines range by measuring the phase shift of a reflected modulated laser beam. The color video camera provides 480x512 red, green, and blue images, with eight bits of intensity per pixel. The field of view (38° vertical and 50° horizontal) and focus of the camera are kept fixed.

The laser range scanner, developed by the Environmental Research Institute of Michigan (ERIM), creates a "range image" of the scene in front of Alvin. The scanner provides a 64x256 array of eight bit range values at a rate of two frames per second. The field of view is 30° vertical by 80° horizontal. Range is calculated by the scanner by measuring the phase shift of a reflected modulated laser beam, directed by a pair of rotating mirrors. The resolution of range values are good to about three inches. Because of the phase difference between two signals to measure distance, the range values obtained are relative and inherently ambiguous - objects whose distance to the sensor differ by exactly one modulation cycle have the same range value. For the ERIM sensor, the distance corresponding to one modulation cycle (the ambiguity interval) is 64 feet.

Alvin currently uses a variety of different computers, and the computer architecture has been designed to facilitate the integration of additional machines as necessary. The diverse processing requirements were met by designing a modular multiprocessor architecture. In the "first generation" ALV hardware, VITS is hosted on a Vicom image processor, while the other software subsystems are hosted on an Intel multiprocessor system. VITS communicates with the other subsystems across a dedicated communication channel.

The vision subsystem is composed of three basic modules: VITS, the vision executive, which handles initialization, sets up communication channels, and "oversees" the processing; VIVD, the video data processing unit; and VIRL, the range data processing unit. The task of the vision subsystem in road-following is to process color or range images to produce a description of the road in front of the vehicle. This description is passed to the reasoning subsystem, which uses additional data such as current position, speed, and heading to generate a trajectory for Alvin to follow.

Communication between the vision subsystem and Reasoning takes place in two basic forms: the scene model and the position update. The scene model is the output of the vision subsystem after each image frame is processed. The scene model contains a record of Alvin's position and heading at the time of image acquisition, and a description of the road found in the image. The description of the road consists of lists of points denoting left

and right edges of the road, as well as points surrounding obstacles. The points are given as 3D positions with respect to the vehicle center of gravity at the time the imagery was acquired. The reasoning subsystem must then transform the road description into a fixed, world coordinate system for navigation.

VITS must know the position and heading of the vehicle at the time of image acquisition to integrate sensor information acquired at different times, and to transform vehicle-centered data into world coordinates. In addition, VITS must be able to predict the location of the road in an image, given its location in the preceding image. These are effected by means of a position update message passed from Reasoning to the vision subsystem. The position update contains information on the current vehicle speed, position, and heading. Synchronization of position update and image acquisition is mediated by a position update request.

The Reasoning subsystem is the executive controller of the ALV, and Vision is a resource of Reasoning. At the highest level, Reasoning is responsible for receiving goals from a human test conductor, creating a plan script to accomplish the goals, and coordinating the other subsystems on Alvin to perform the necessary tasks.

Because the processing involved in creating a visual description of the environment is beyond the real-time capability of present computers, the scene model is not used directly in the vehicle's control servo loop. Instead, the Navigator (part of the reasoning subsystem) pieces together scene models from the vision system and builds a reference trajectory that is sent to the Pilot for control. The reasoning subsystem accepts a position update request from VITS, generates the appropriate data, and sends a position update to VITS. Upon receipt of a scene model, Reasoning evaluates it and plots a smooth trajectory if the data is acceptable. The new trajectory is computed to smoothly fit the previous trajectory.

The Pilot performs the actual driving of the vehicle. Given a trajectory from Reasoning, the Pilot computes the error values of lateral position, heading and speed by comparing LNS data with the target values specified in the trajectory. The Pilot uses a table of experimentally obtained control gains to determine commands needed to drive the errors towards zero; these commands are output to the vehicle controllers. The vision subsystem has no direct communication with the Pilot.

Figure 26 illustrates Martin-Marietta's contributions towards development of functionalities identified in Figure 7.

Required Functionalities	Levels of Autonomy					
	Telepresence	Teleoperation	Teleassistance	Guided Robotics	Supervised	Autonomous
Mission Sensors				MMC	MMC	
Mission Related Perception				MMC	MMC	
Navigation Sensors				MMC	MMC	
Navigation Perception				MMC	MMC	
Navigation Planning					MMC	
Mission Planning						
Path Planning				MMC	MMC	
Local Planning				MMC	MMC	
Reactive Planning/Obstacle Avoidance				MMC	MMC	
World Model					MMC	
Environment Model				MMC	MMC	
Sensor Preprocessing		MMC	MMC	MMC	MMC	
Computer Vision Architectures				MMC	MMC	
High Bandwidth Communication				MMC		
Low Bandwidth Communication					MMC	
MMI		MMC	MMC	MMC	MMC	
Vehicle Model				MMC	MMC	
Integrating Architectures		MMC	MMC	MMC	MMC	
Actuators		MMC	MMC	MMC	MMC	
Mobility Platforms		MMC	MMC	MMC	MMC	MMC

Figure 26. Martin-Marietta Corporation's Contribution Towards the Functionalities Defined in Figure 7*

* Martin Marietta is and has been a systems integrator for unmanned ground vehicles. This summary includes developments by subcontractors which Martin Marietta has integrated into unmanned vehicle systems.

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